Beta Beams,
EUROnu WP4

SEVENTH FRAMEWORK
PROGRAMME

Beta Beams
Implementation at CERN

Christian Hansen
NUFACT11, CERN, 2011/8/5

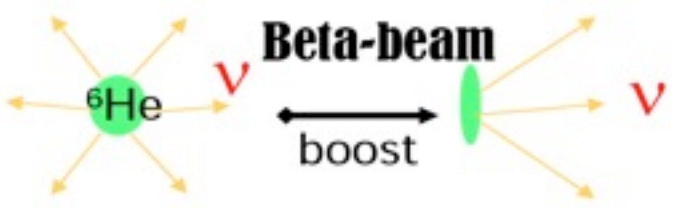
On behalf of the Beta Beam Collaboration

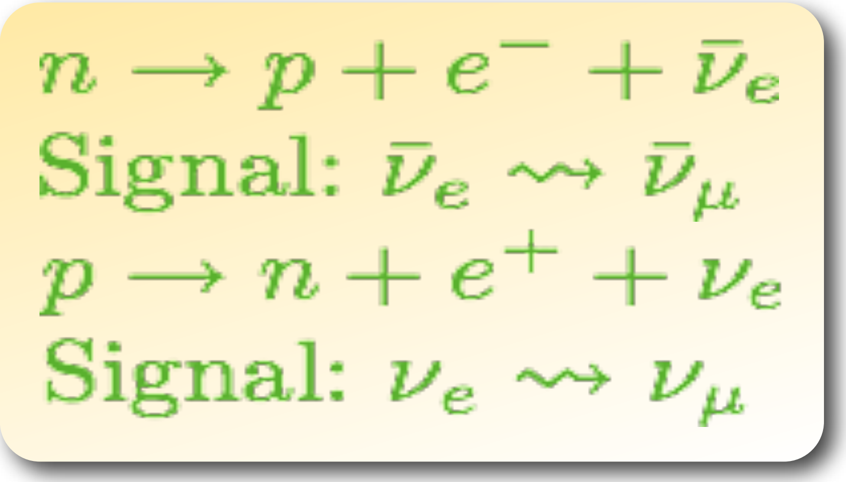
Outline

- BETA BEAMS
  - Overview
  - Beta Beam Components
  - Intensities
  - Impact of large θ_{13}
- Summary

Beta Beams - Basic Idea

- **Basic idea (*Phys. Let. B, 532 (2002) 166-172, P. Zucchelli*):**
  - **Accelerate radioactive ions to high γ**
  - **Let them β-decay in a Decay Ring (DR)**
  - **The DR has one straight section pointing in the direction of a detector**
  - **ν-beam with opening angle 1/γ and with known energy and ν-species**
  - **Two different ion types; β^+ decaying (gives ν_e) and β^- decaying (gives $\overline{\nu}_e$)**



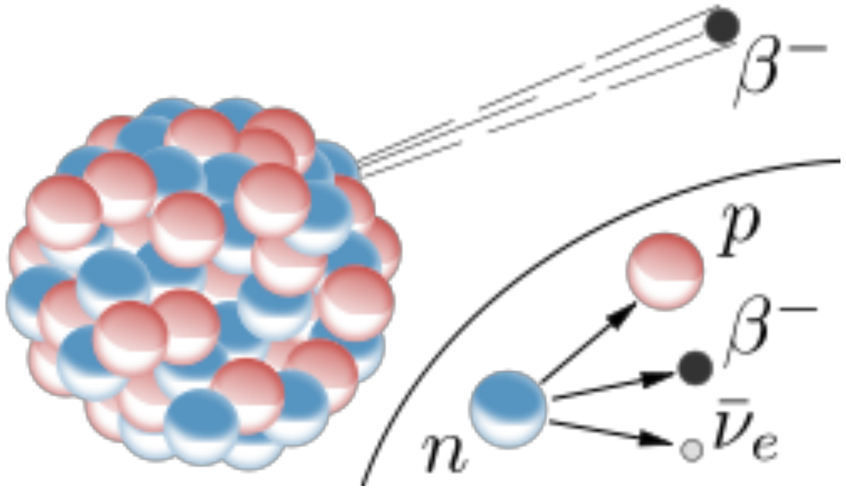


$$n \longrightarrow p + e^- + \bar{\nu}_e$$

$$\text{Signal: } \bar{\nu}_e \rightsquigarrow \bar{\nu}_\mu$$

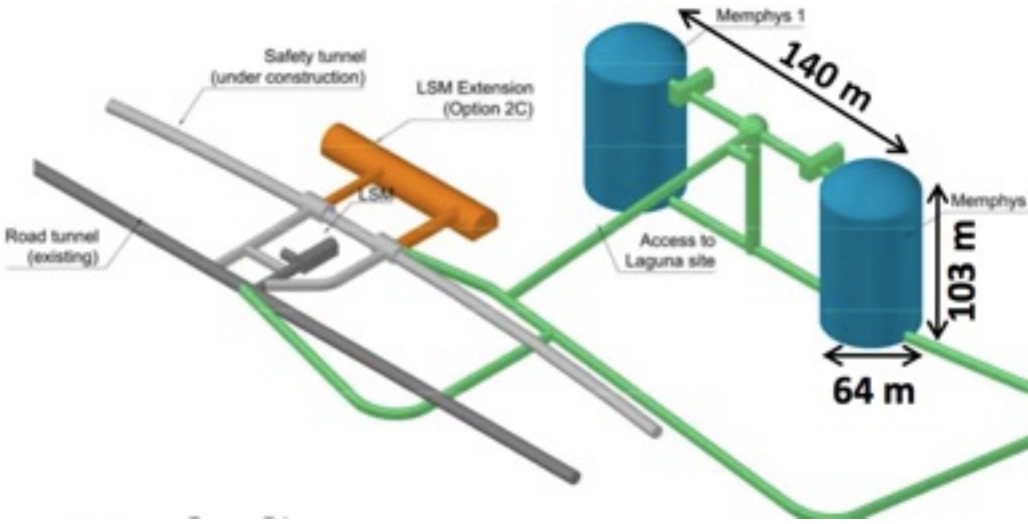
$$p \longrightarrow n + e^+ + \nu_e$$

$$\text{Signal: } \nu_e \rightsquigarrow \nu_\mu$$



- **Detector:**
  - **No need for magnetic detector since only have to distinguish μ^+ and e^+ (μ^- and e^-)**

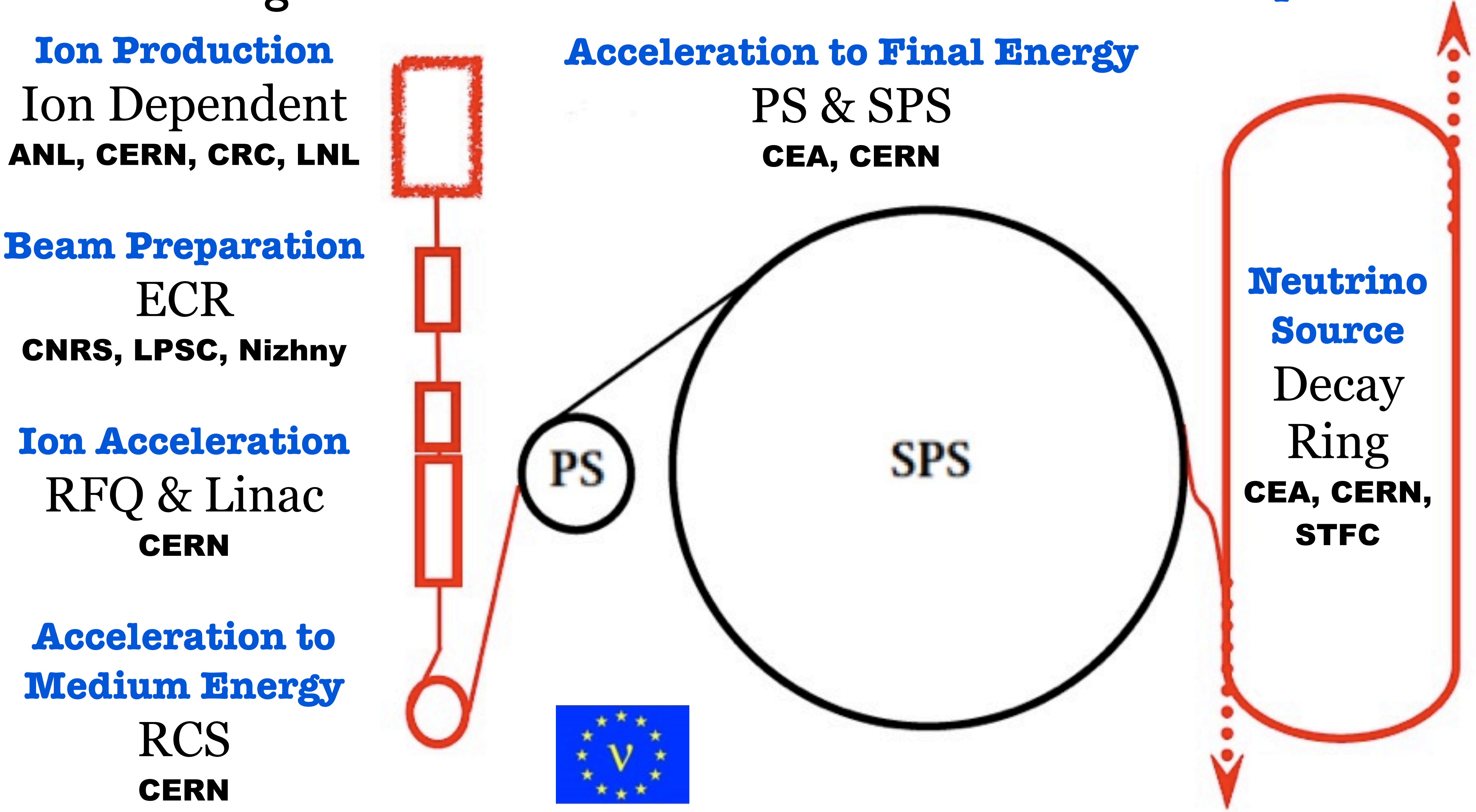
E.g. Water Čerenkov:



Beta Beams at CERN

Beta Beams at CERN

… is being studied all over the world:



Experiment

Ion Production
Ion Dependent
ANL, CERN, CRC, LNL

Beam Preparation
ECR
CNRS, LPSC, Nizhny

Ion Acceleration
RFQ & Linac
CERN

Acceleration to Medium Energy
RCS
CERN

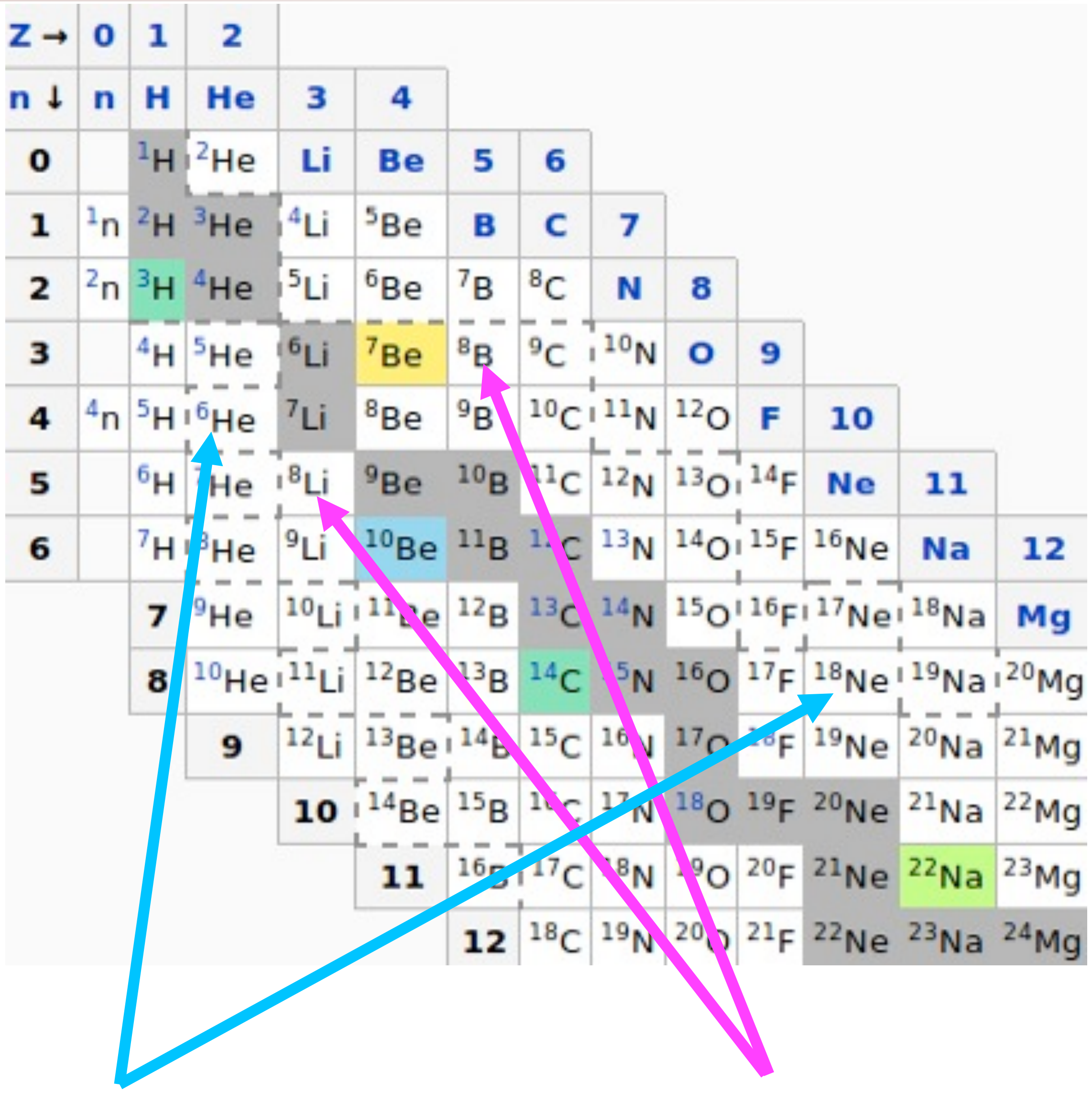
Acceleration to Final Energy
PS & SPS
CEA, CERN

Neutrino Source
Decay Ring
CEA, CERN, STFC

- Groups with synergetic projects joining continuously
  - ➡ E.g. **ANL** (USA), **STFC** (UK), **GSI** & **Aachen** (DE), **Weizmann** (IL)
- Specially interesting with T2K's large θ_{13} !! (below)

Choice of Ions

- **Considerations**
  - **Pair of β⁺ and β⁻ active ions**
    for ν and anti-ν …
  - **Production rates**
    isol method or production ring
  - **Life time**
    optimized for baseline ~1s
  - **Reactivity**
    noble gases are good
  - **Low Z preferred**
    minimize accelerated mass per charge
    reduce space charge problems
  - **Q value**
    defines ν-energy & baseline



Z →	0	1	2										
n ↓	n	H	He	3	4								
0		^{1}H	^{2}He	Li	Be	5	6						
1	^{1}n	^{2}H	^{3}He	^{4}Li	^{5}Be	B	C	7					
2	^{2}n	^{3}H	^{4}He	^{5}Li	^{6}Be	^{7}B	^{8}C	N	8				
3		^{4}H	^{5}He	^{6}Li	^{7}Be	^{8}B	^{9}C	^{10}N	O	9			
4	^{4}n	^{5}H	^{6}He	^{7}Li	^{8}Be	^{9}B	^{10}C	^{11}N	^{12}O	F	10		
5		^{6}H	He	^{8}Li	^{9}Be	^{10}B	^{11}C	^{12}N	^{13}O	^{14}F	Ne	11	
6		^{7}H	He	^{9}Li	^{10}Be	^{11}B	C	^{13}N	^{14}O	^{15}F	^{16}Ne	Na	12
		7	^{9}He	^{10}Li	Be	^{12}B	^{13}C	^{14}N	^{15}O	^{16}F	^{17}Ne	^{18}Na	Mg
		8	^{10}He	^{11}Li	^{12}Be	^{13}B	^{14}C	N	^{16}O	^{17}F	^{18}Ne	^{19}Na	^{20}Mg
			9	^{12}Li	^{13}Be	^{14}B	^{15}C	^{16}N	^{17}O	F	^{19}Ne	^{20}Na	^{21}Mg
				10	^{14}Be	^{15}B	C	N	^{18}O	^{19}F	^{20}Ne	^{21}Na	^{22}Mg
					11	^{16}B	^{17}C	N	O	^{20}F	^{21}Ne	^{22}Na	^{23}Mg
						12	^{18}C	^{19}N	O	^{21}F	^{22}Ne	^{23}Na	^{24}Mg

“Low Q”

“High Q”

Isotope	^{18}Ne	^{6}He	^{8}B	^{8}Li
A/Z	1.8	3	1.6	2.7
Emitter	β⁺ (ν)	β⁻ (anti-ν)	β⁺ (ν)	β⁻ (anti-ν)
$\tau_{1/2}$ [s]	1.67	0.81	0.77	0.83
Q [MeV]	3.3	3.5	13.9	13.0

“Q value” is the kinetic energy release of a particle at rest

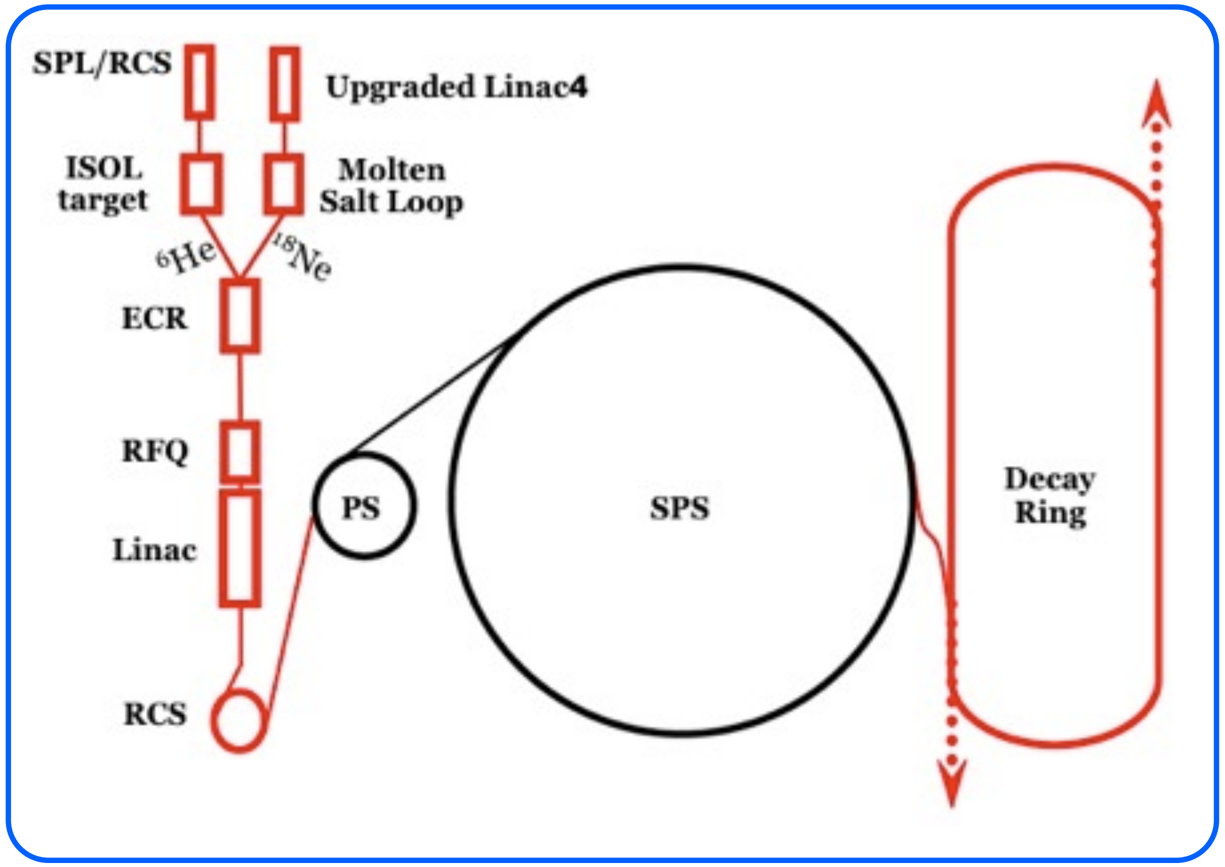
E.g. for the neutron decay

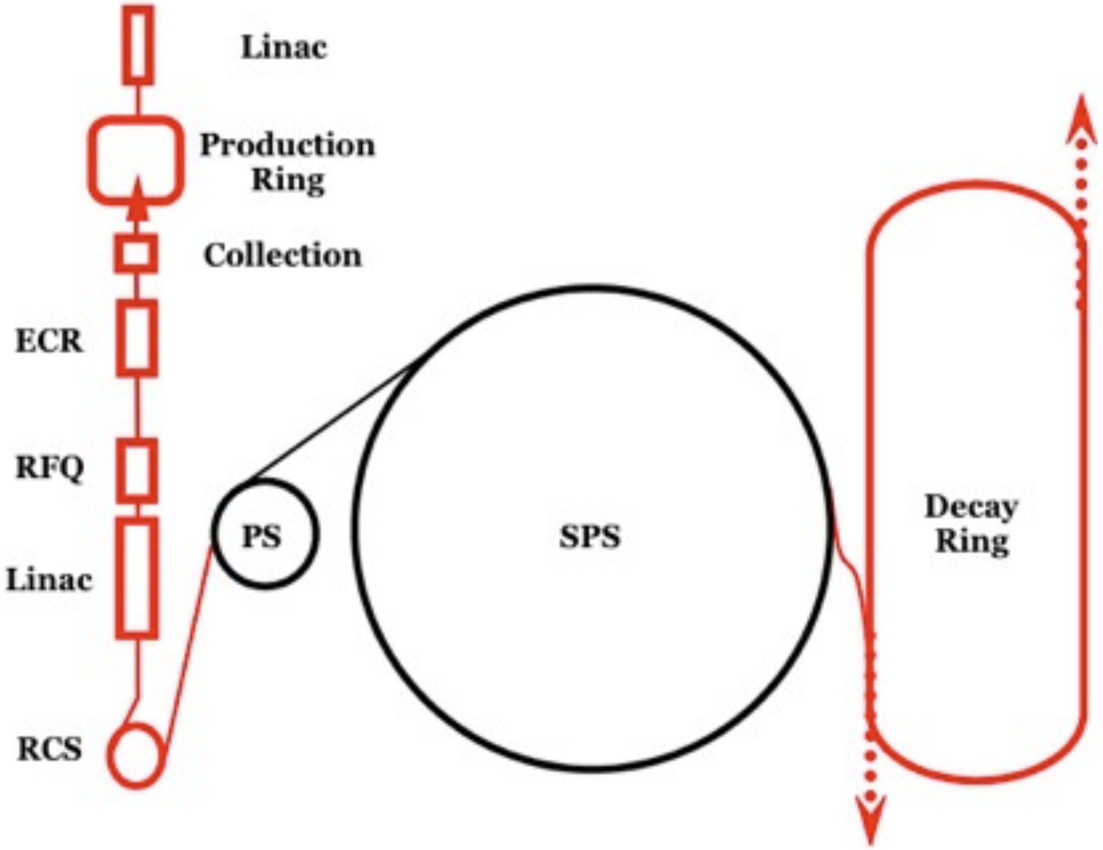
$$Q = m_n - m_p - m_{\bar{\nu}} - m_e$$

Two Baselines

BB OVERVIEW

- **Currently two different baselines** (both with γ=100) **are under investigation**
- **^{6}He & ^{18}Ne: L ≈ 130 km**
- **^{8}Li & ^{8}B: L ≈ 650 km**





Chosen as EUROnu's baseline

Outline

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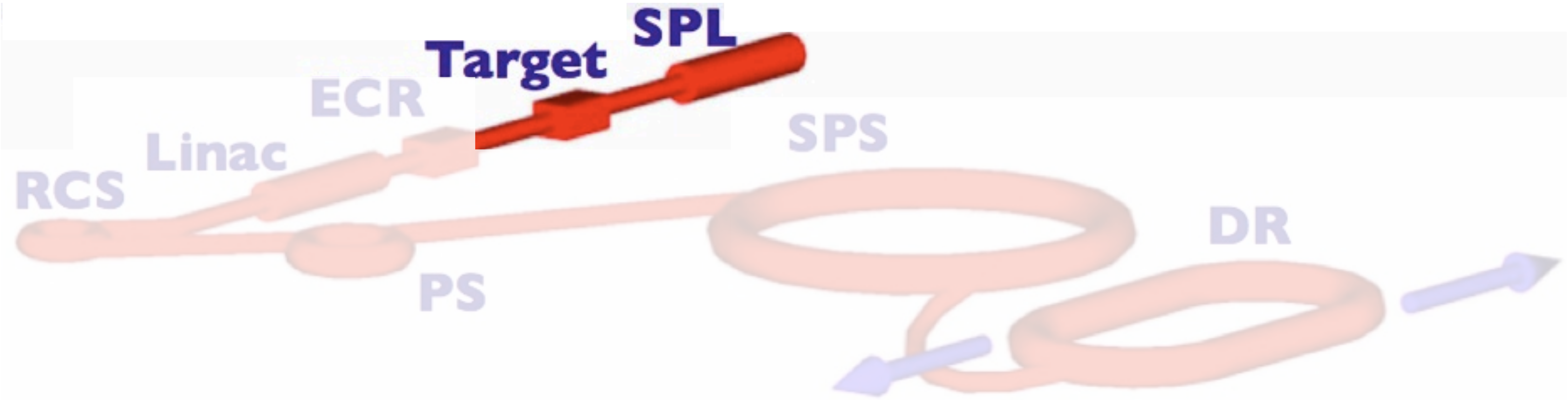
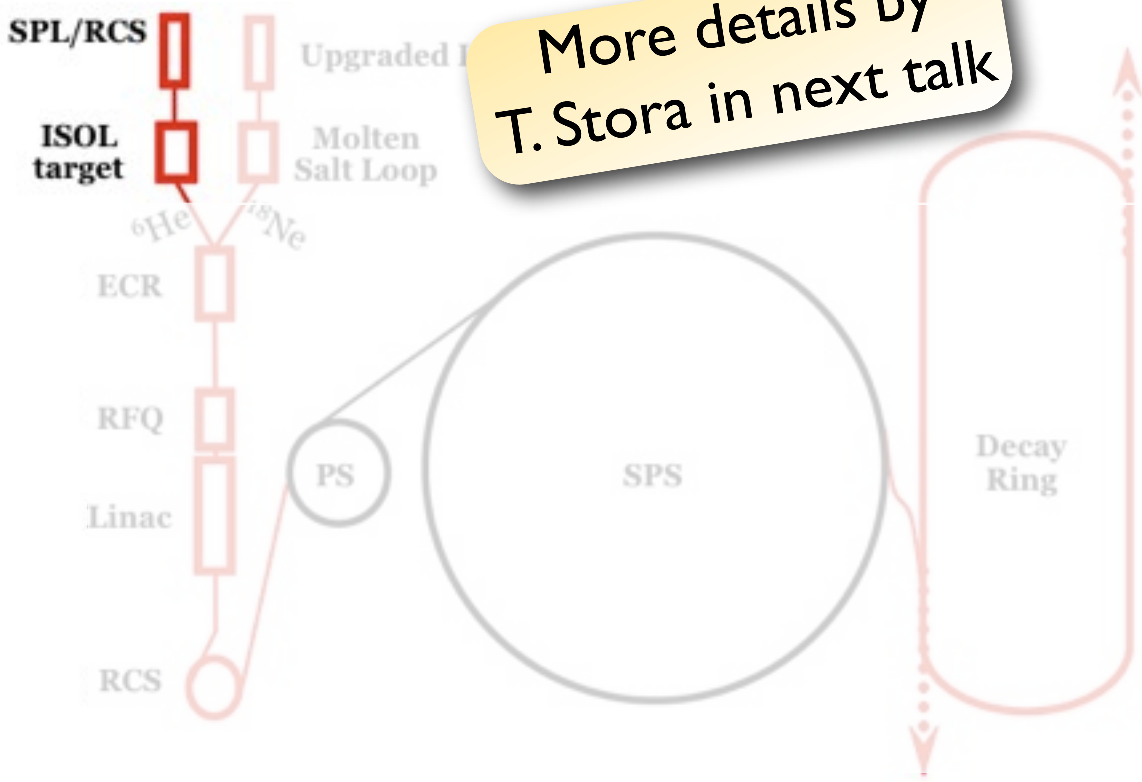
Ion Production

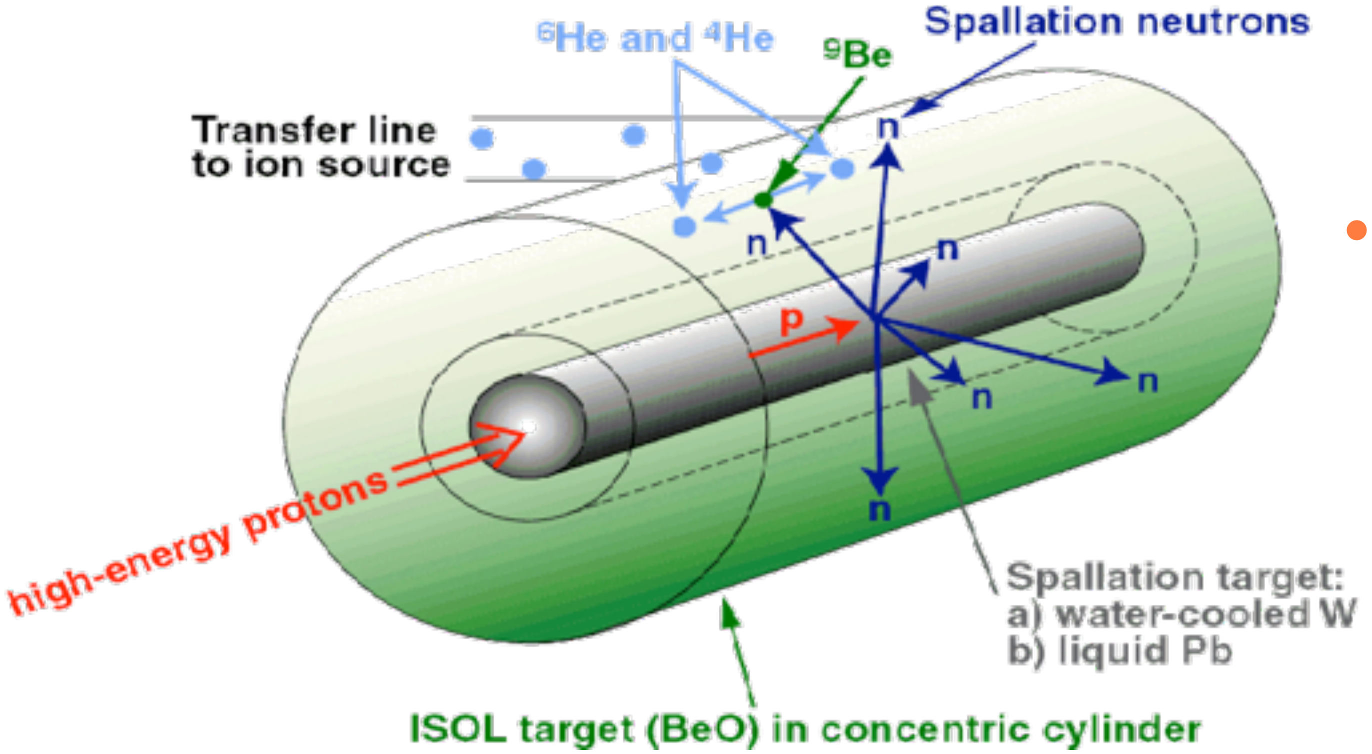


Low Q Ion Production (^{6}He)

- **ISOL Method:** www.cern.ch/isolde
  - **High energy protons from an SPL** (200kW & 2GeV) **or an RCS** (20kW & 2GeV)
    - Possibly built for LHC upgrade
    - Hie-ISOLDe would benefit
  - **Spallation Target: W or Pb**
  - **Spallation Neutrons react in the ISOL Target (BeO)**
  - **^{6}He is produced & transferred to ECR**

More details by T. Stora in next talk





- **Standard ISOLDE Method**
  - $\approx 5 \cdot 10^{13}\ {}^6He/s$

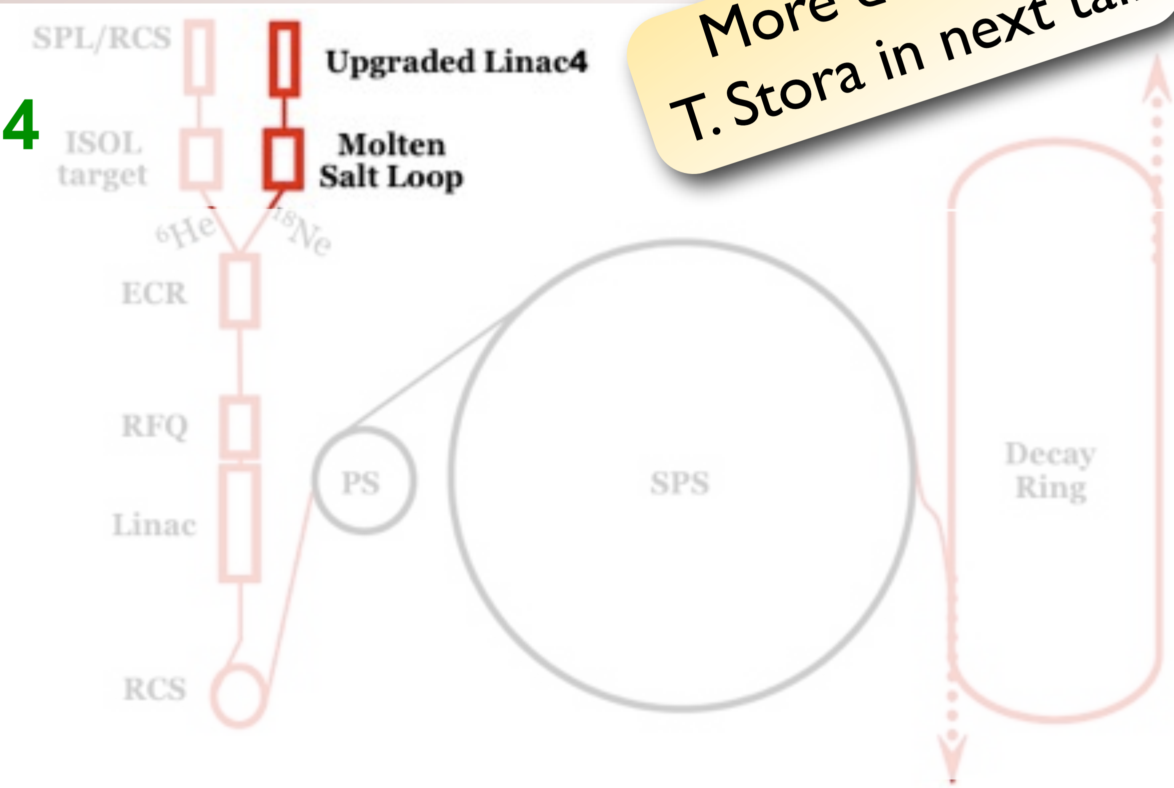
→ **~ enough anti-ν** ☺

Low Q Ion Production (^{18}Ne)

- **Molten Salt Loop:** T. Stora
  - 160 MeV protons by upgraded Linac4
  - hit NaF salt loop → 2 reactions;

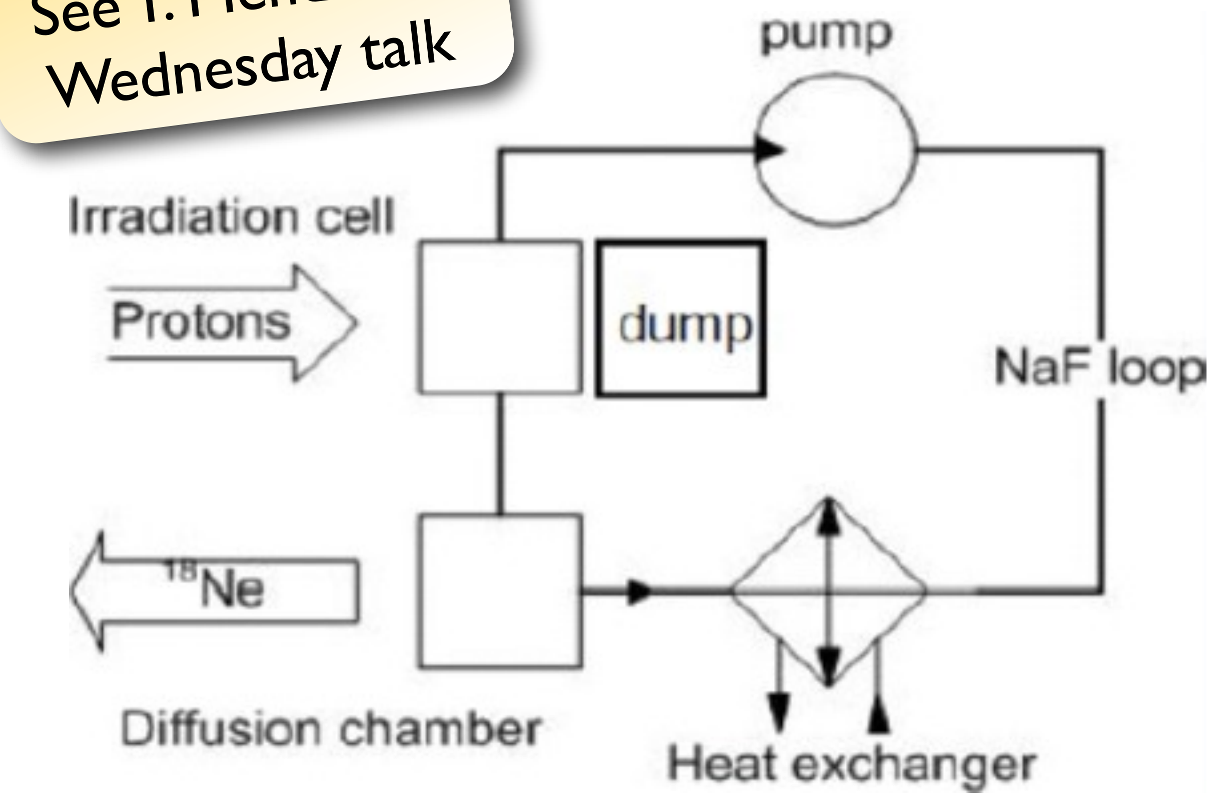
$$\boxed{\begin{gathered} ^{19}F(p,2n)^{18}Ne \\ + \\ ^{23}Na(p,X)^{18}Ne \end{gathered}}$$

  - Then ^{18}Ne diffused to the ECR



More details by T. Stora in next talk

See T. Mendoca's Wednesday talk



- Studies claim
  - 1MW target station would give
  - $\boxed{\approx 1.2 \cdot 10^{13}\ ^{18}Ne/s}$

  → ~ enough ν ☺
  - → only 2 times more power than CNGS operating target station

- Experiment scheduled in November at CERN

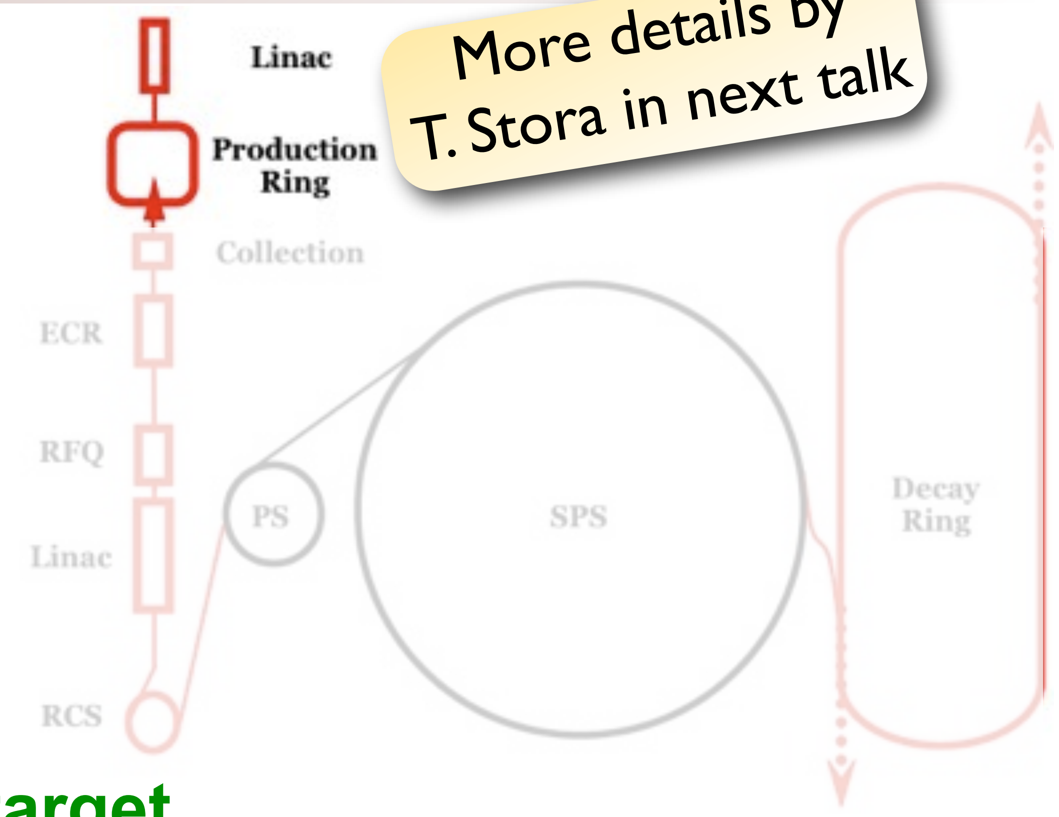
High Q Ion Production (^{8}Li & ^{8}B)

- **^{8}Li (*Nucl. Inst. A, 568 (2006) 475-487, C. Rubbia*):**
  - **25 MeV ^{7}Li ions enters Production Ring → Multiple passes through a wedge-shaped gas-jet deuterium target → ion-cooling, stripping & production;**

$$^2_1H + ^7_3Li \rightarrow ^8_3Li + p$$

  - **Difficulties to reach target density**

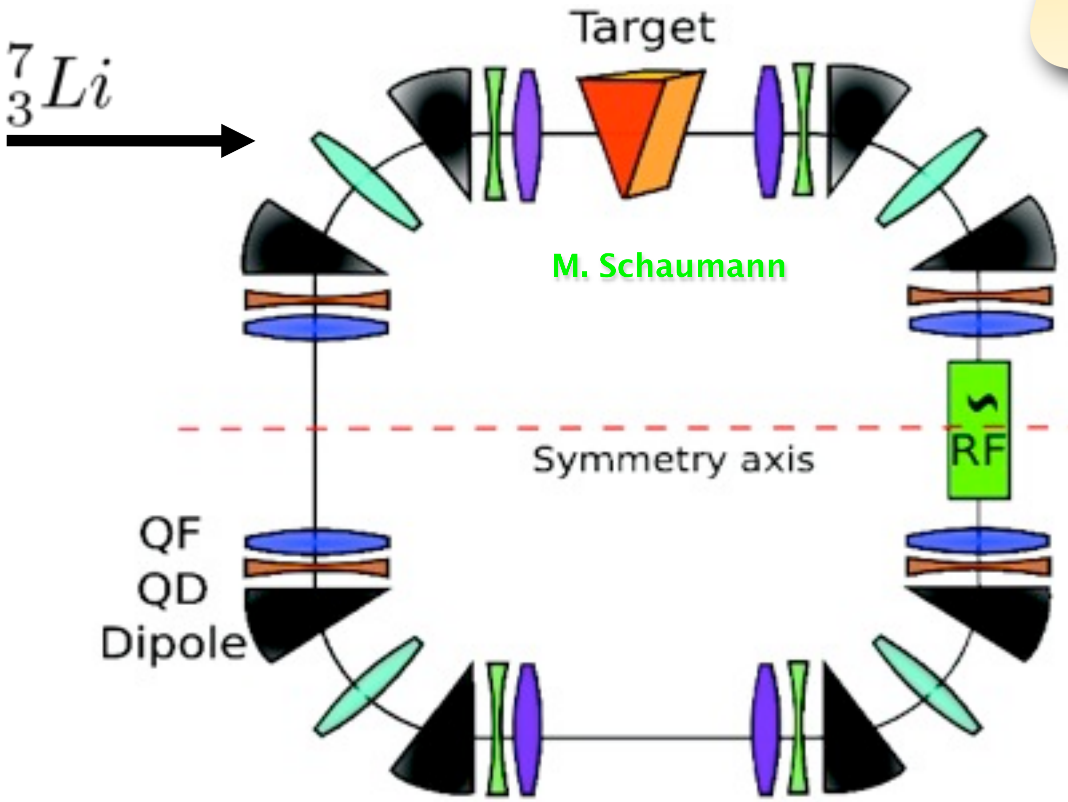
E. Benedetto



More details by T. Stora in next talk

- **New: direct kinematics with liquid ^{7}Li film target**

See J Nolen's Wednesday talk



- **^{8}B:** Same with

$$^3_2He + ^6_3Li \rightarrow ^8_5B + n$$

but cross-section and angular distribution needs to be studied: next slide

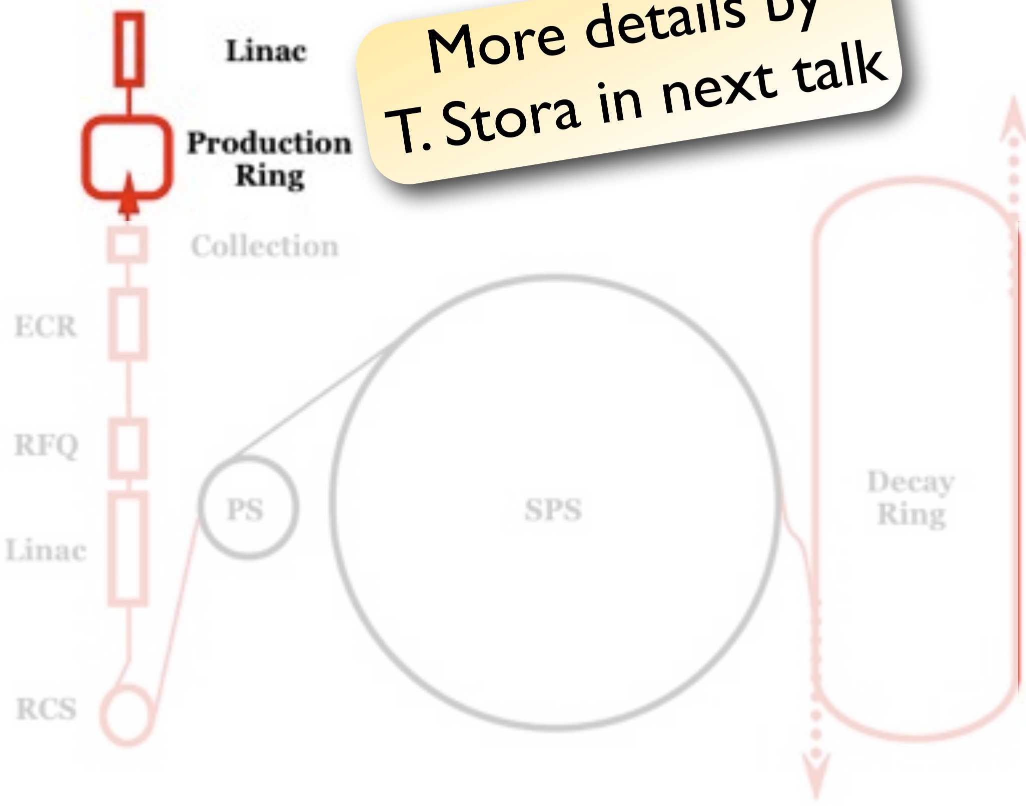
^{8}B Experiment at LNL

V.L. Kravchuk

- ^{8}B; The reaction (6.1 MeV)

$$^{3}_{2}He +^{6}_{3} Li \rightarrow^{8}_{5} B + n$$

was studied at LNL June 2011



More details by T. Stora in next talk

CN proposal: BETABEAM

^{8}B PRODUCTION MEASUREMENT FOR THE FP7 BETA BEAM DESIGN STUDY

V.L. Kravchuk[1], **E. Wildner[2]**, M. Cinausero[1], G. De Angelis[1], F. Gramegna[1], T. Marchi[1], G. Prete[1], E. Benedetto[2], C. Hansen[2], G. Collazuol[3], M. Mezzetto[3], G. Derosa[4], V. Palladino[4], E. Vardaci[4]

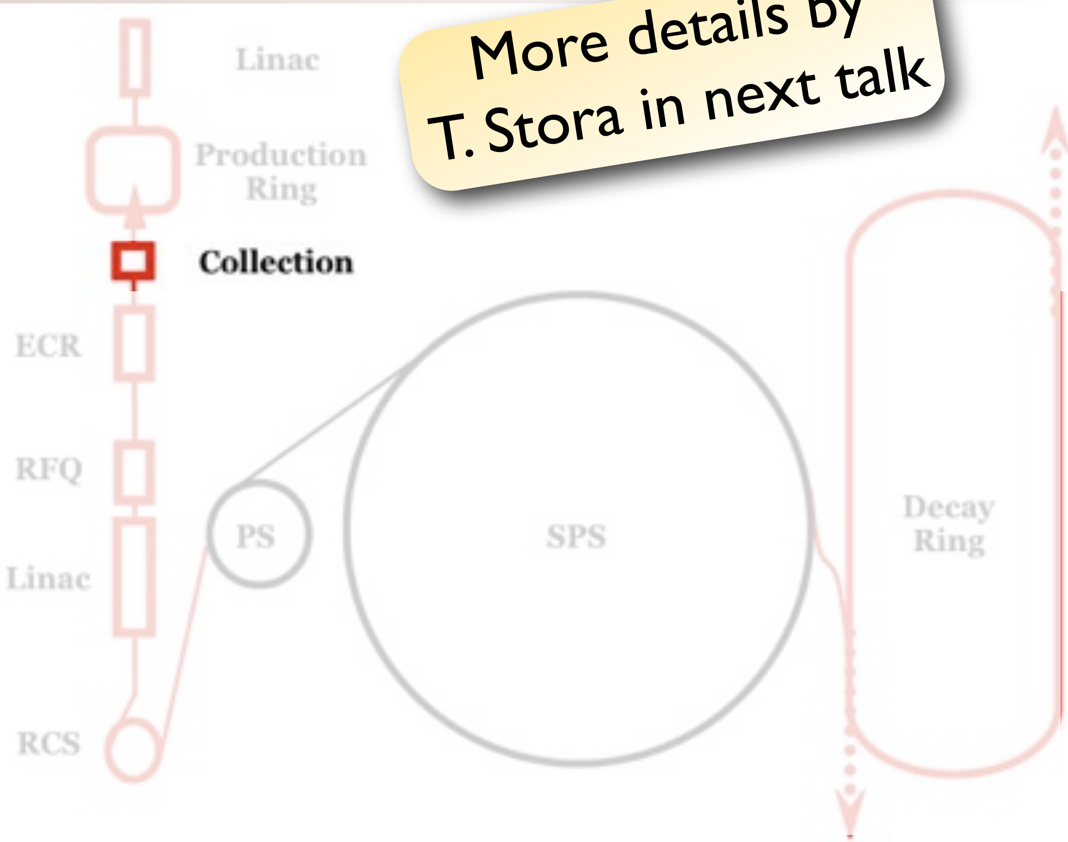
- RipeN setup: 8 BC501 detectors covering 15° → 140°
- 30% more statistics than planned was obtained!
- Resulting cross section and angular distribution from analysis ~ end 2011

High Q Ion Collection (^{8}Li & ^{8}B)

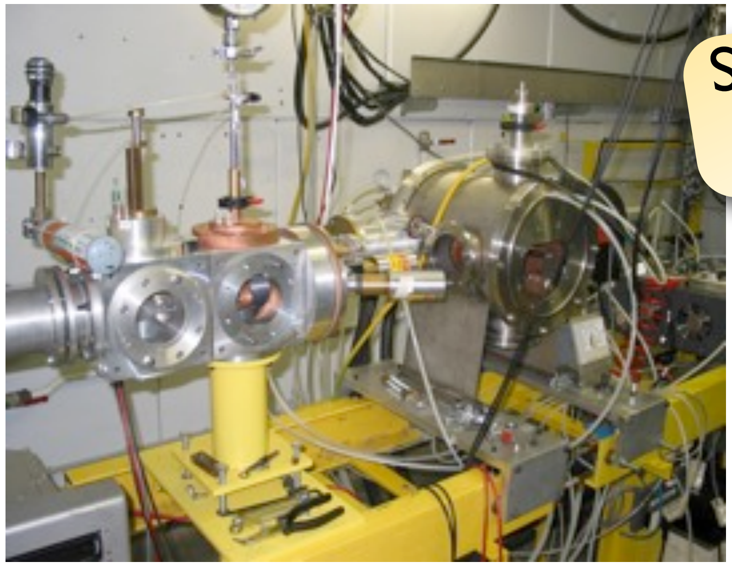
- **^{8}Li and ^{8}B Collection:**

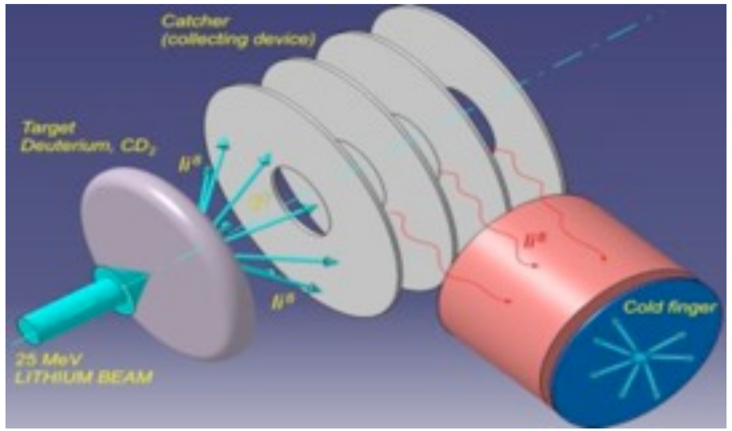
S. Mitrofanov

  - **Ions collected by catcher foils,**
  - **diffused out from oven with a cold finger** (then transferred to ECR)
  - **R&D ongoing:**

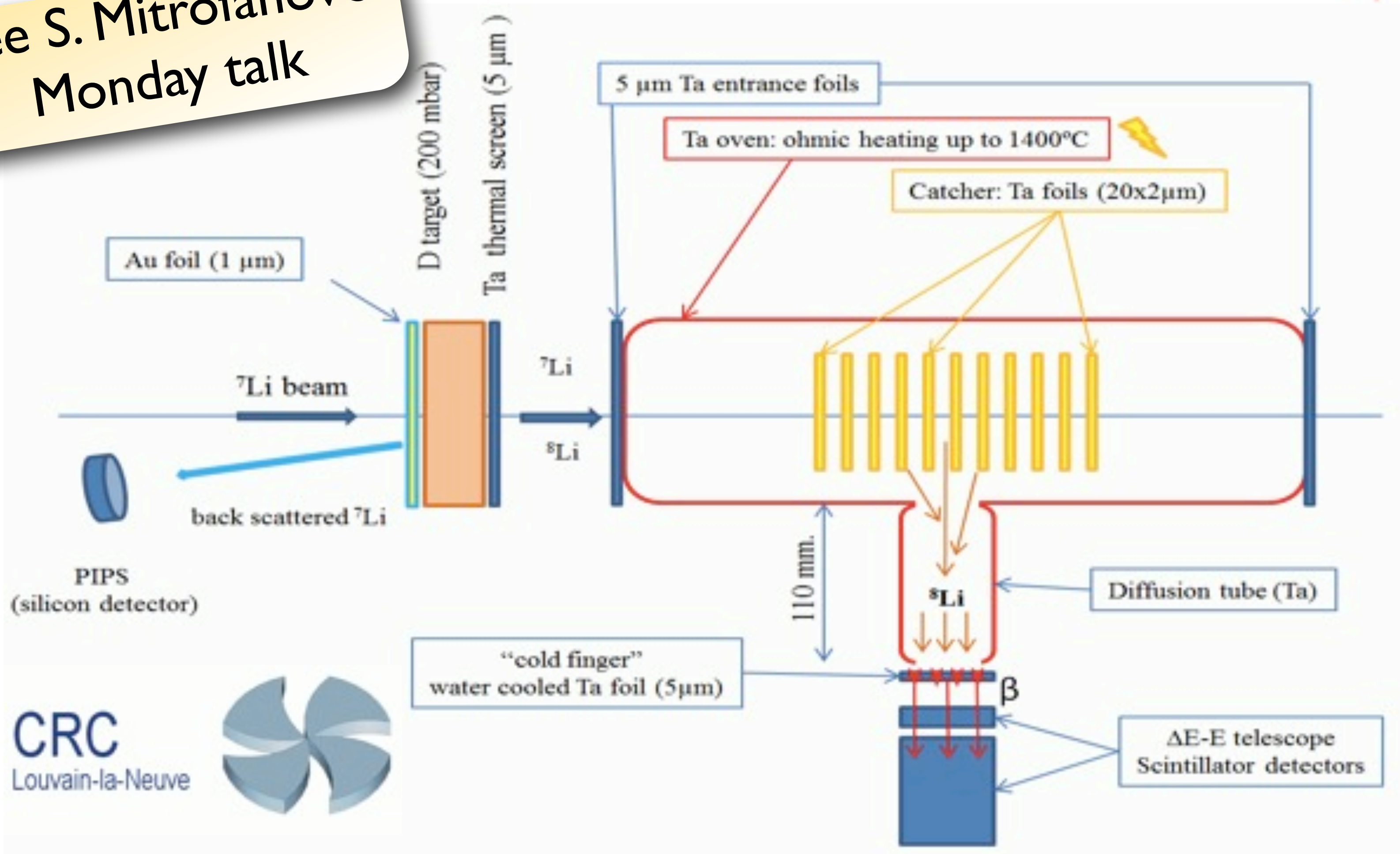


More details by T. Stora in next talk

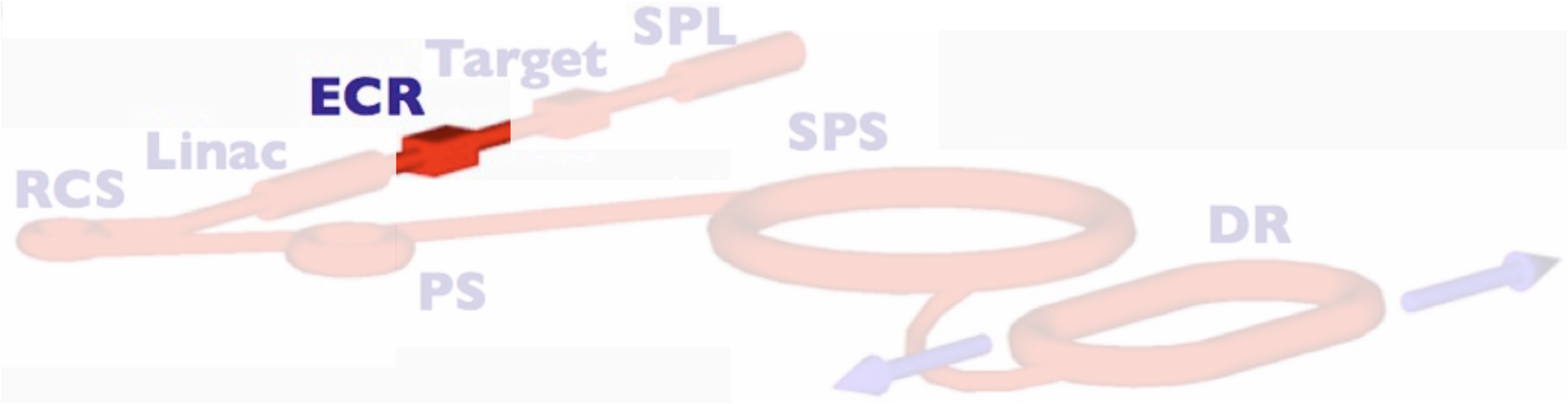




See S. Mitrofanov's Monday talk



ECR Source



ECR (Electron Cyclotron Resonance) Ion Source

- **Radioactive atoms diffuse in to ECR ion source** $\omega_{hf} = \omega_{ce} = eB/m_e$

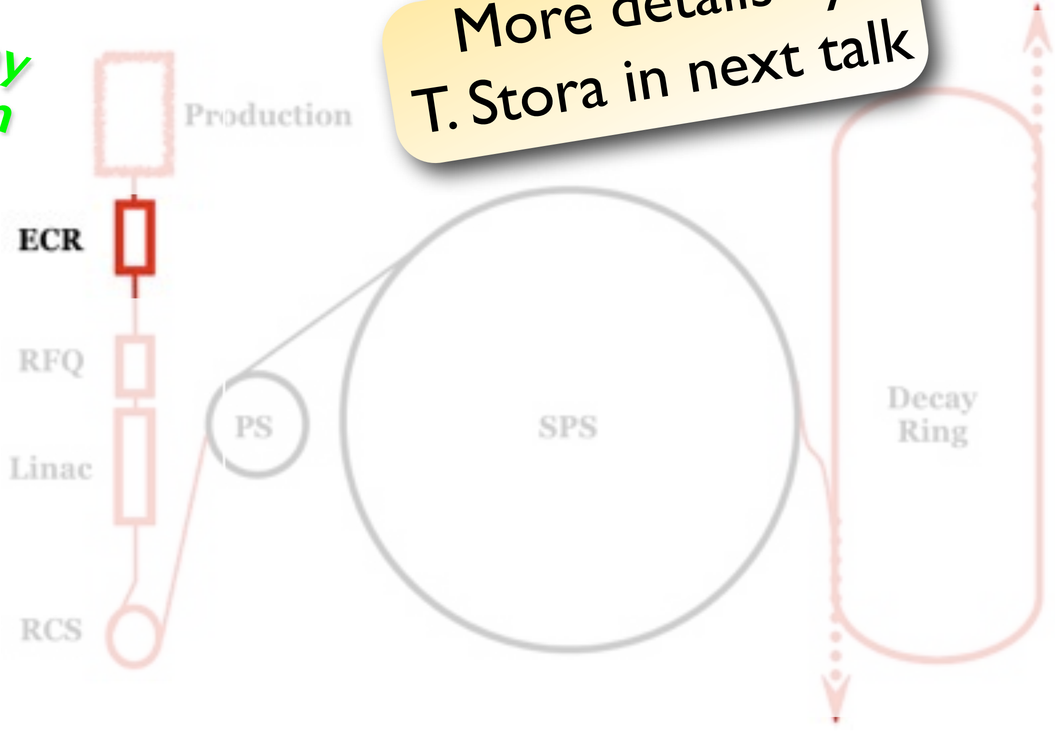
- **Confined plasma → ionization**

- **ECR 60GHz** (highest existing: 28GHz)
  → 50μs pulses with ions to Linac

- **R&D ongoing:**
  - **Magnetic tests** in CNRS, LPSC, Grenoble, T. Lamy
  - **Theory and Short pulsed tests** in Nizhny Novgorod, Russia, V. Zorin

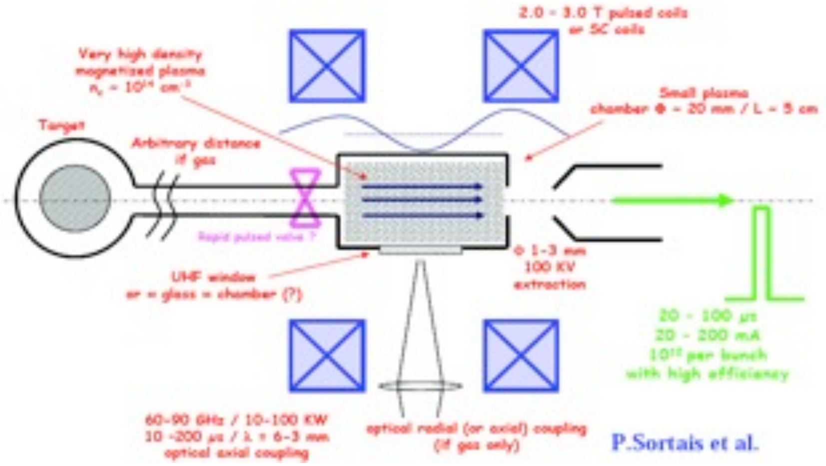
T. Lamy
V. Zorin

More details by T. Stora in next talk

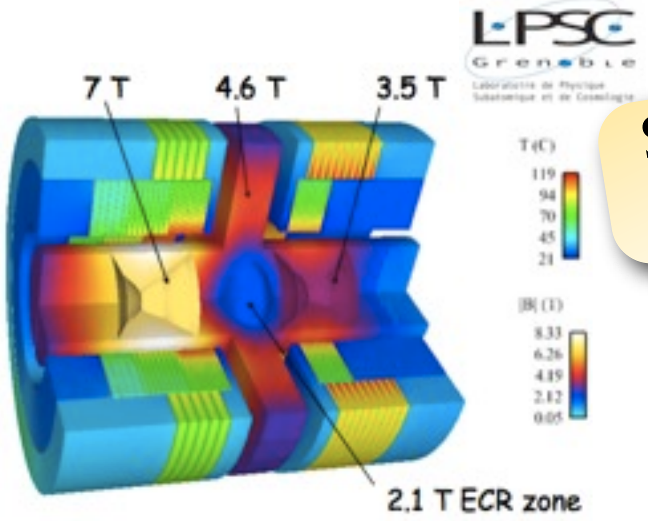


- **Estimated efficiencies:**

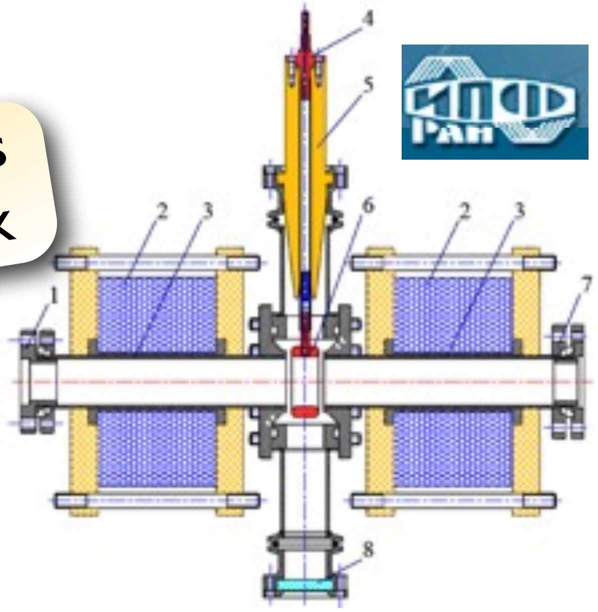
^{6}He: 30% & ^{18}Ne: 20%
^{8}Li & ^{8}B: 3 to 10 times less



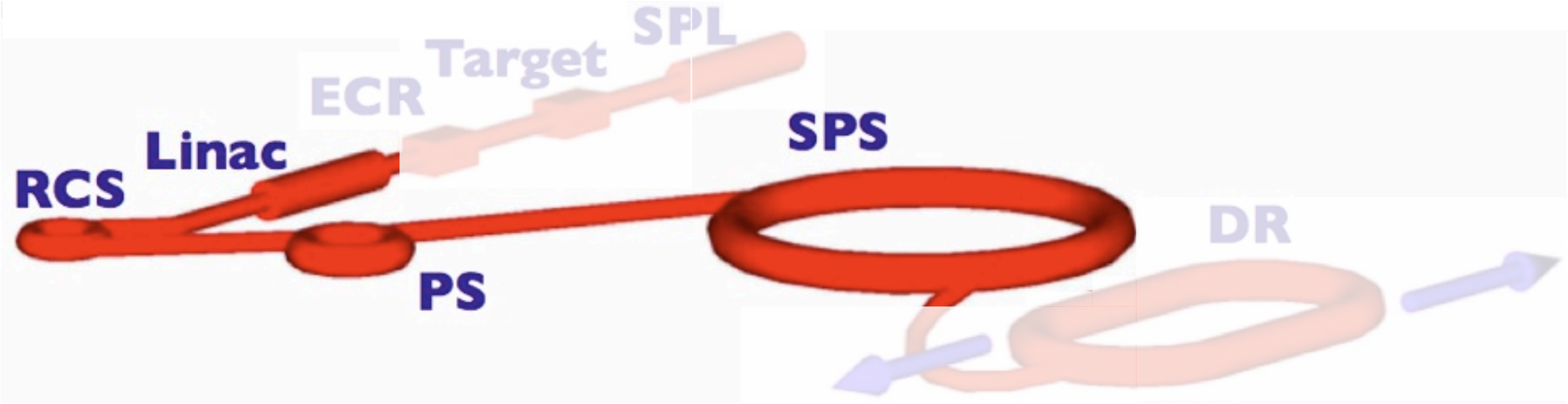
P.Sortais et al.



See T. Lamy's Monday talk



Acceleration and Bunching



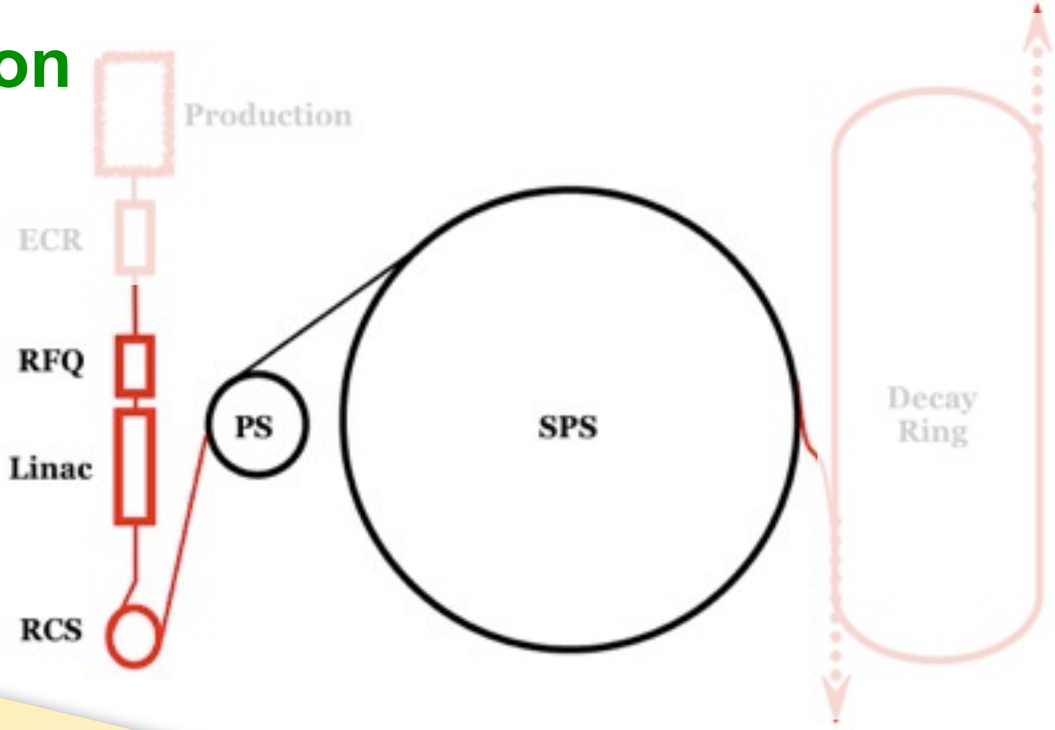
Accelerators

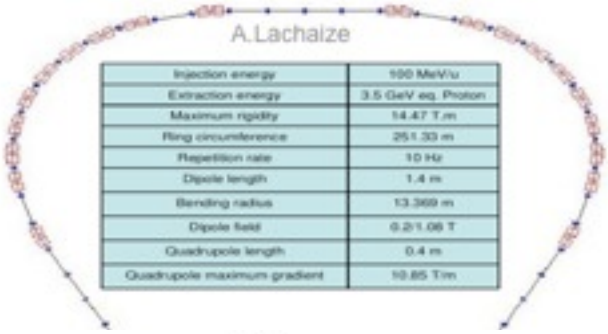
BB COMPONENTS

- **RFQ & Linac: Bunching and Pre-acceleration**
  - **100 MeV/u at ejection**
- **RCS: Intensity increase & acceleration**
  - **Multiturn injection: Squeeze 26 ECR pulses into one bunch; 50% efficiency**
  - **Acceleration to 14.47 Tm**
- **PS: Acceleration**
  - **Collects 20 bunches** (one by one)
  - **Acceleration to 86.7 Tm** (PS max)
- **SPS: Acceleration**
  - **Fast injection of one PS batch** (20 bunches)
  - **PS bunches not shortened** (due to space-charge)
  - **1 MV 40 MHz RF** (added) **for PS bunches**
  - **Bunch shortening, RF swap to** (existing) **8 MV 200 MHz RF & γ-transition**
  - **Acceleration to γ = 100** (not SPS max)

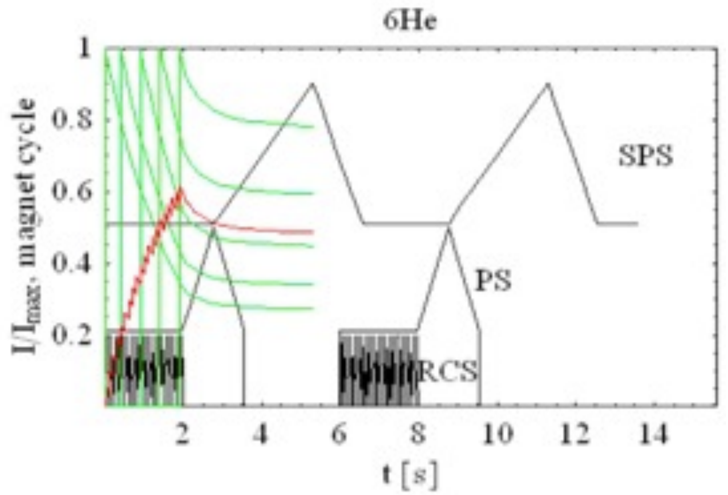
A. Lachaize

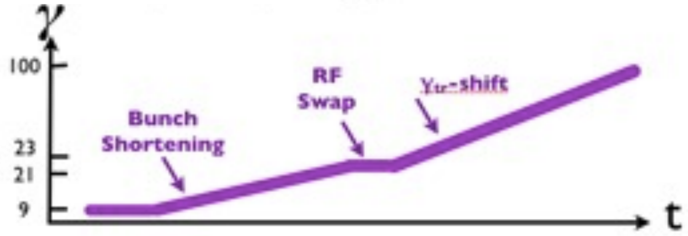
See E. Benedetto's Monday talk



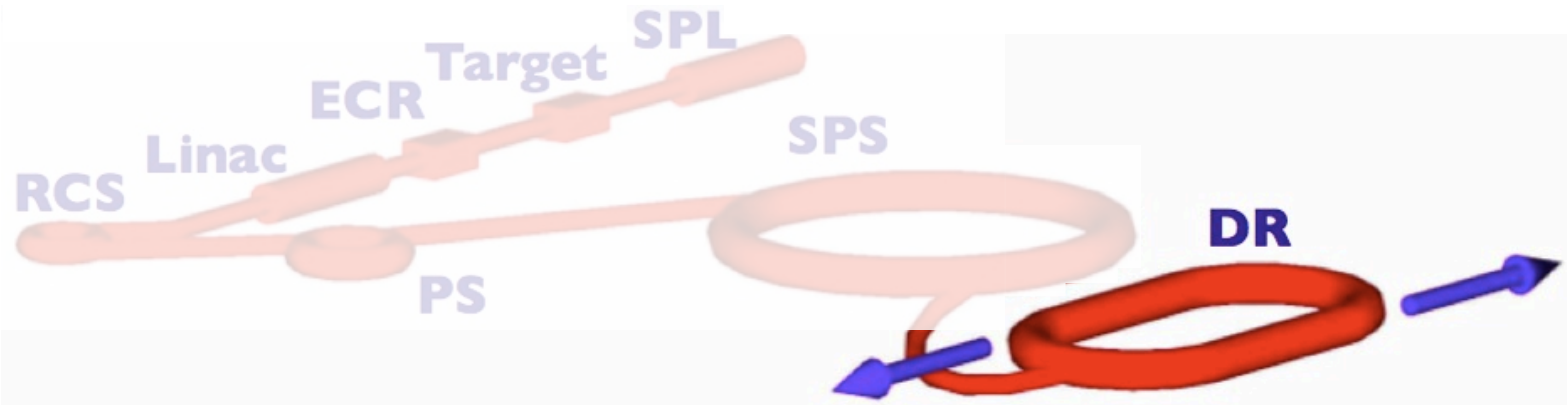


Injection energy	100 MeV/u
Extraction energy	3.5 GeV eq. Proton
Maximum rigidity	14.47 T.m
Ring circumference	251.33 m
Repetition rate	10 Hz
Dipole length	1.4 m
Bending radius	13.369 m
Dipole field	0.2/1.08 T
Quadrupole length	0.4 m
Quadrupole maximum gradient	10.85 T/m



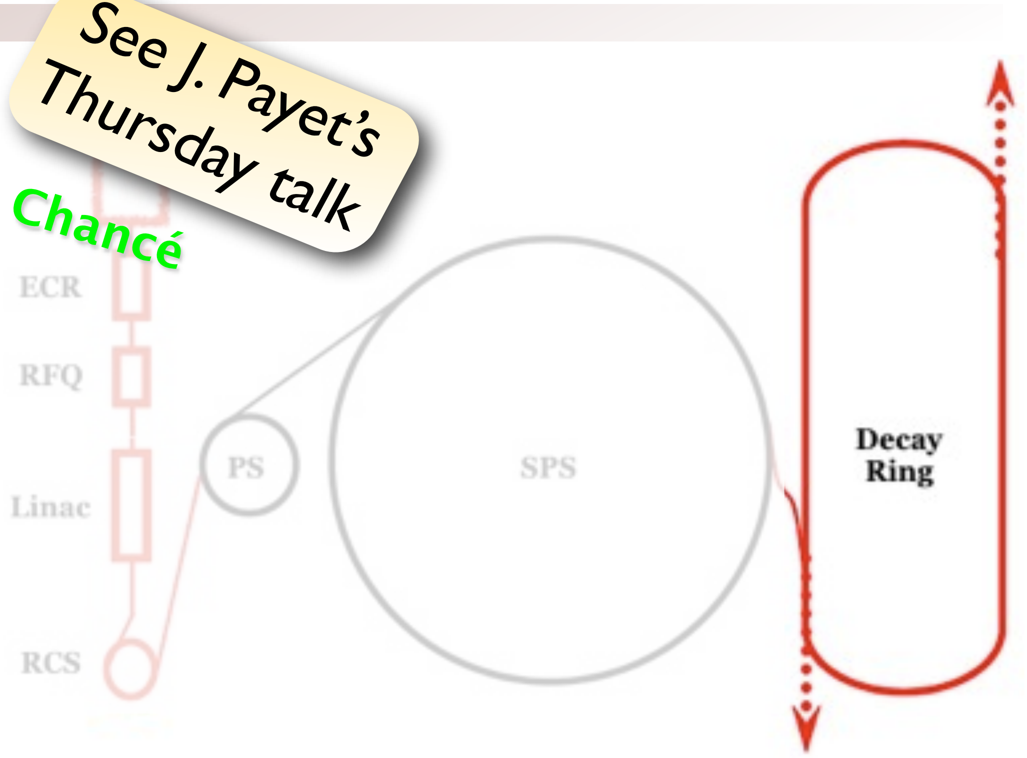


DR



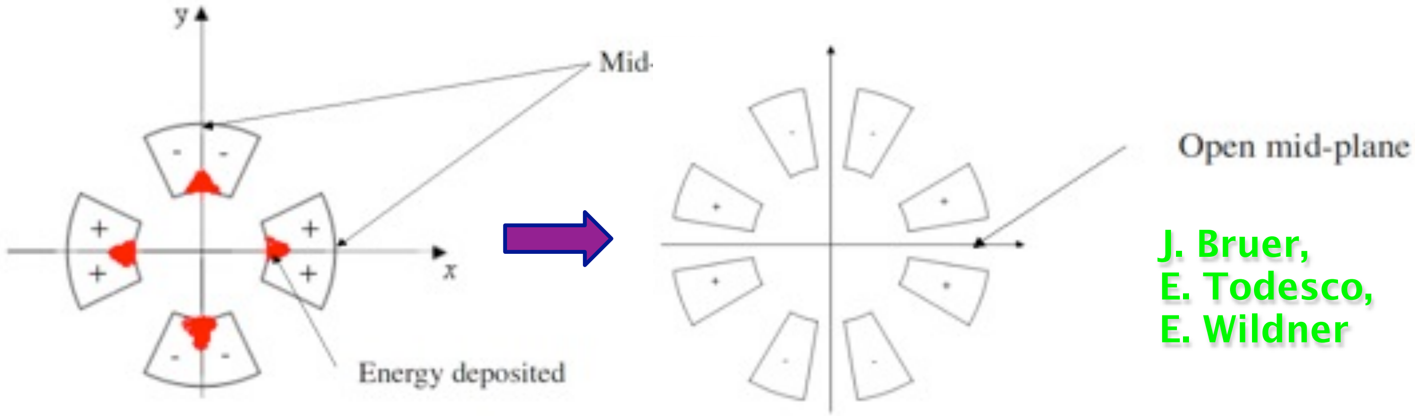
DR - Decay Ring

- **For both Baselines:**
  - **Circumference = 6911.6m & L_{eff} = 39%**
  - **Bending radii ρ = 121m →** B = 4 - 8 T
  - **Superconducting → Open mid-plane quadrupoles to avoid quenching** due to energy depositions from decays



See J. Payet's Thursday talk

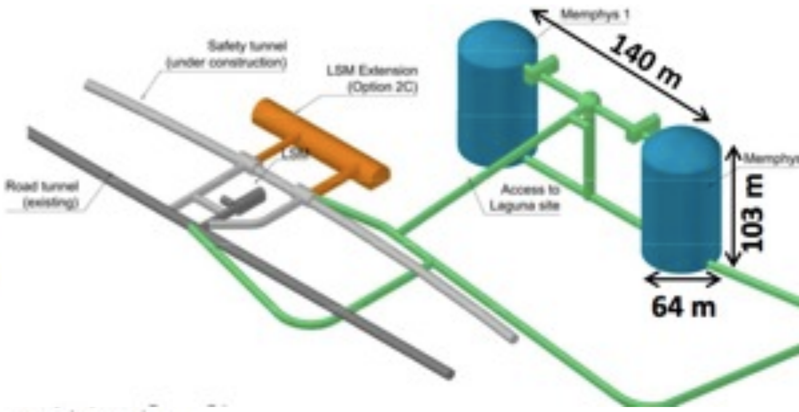
A. Chancé



J. Bruer,
E. Todesco,
E. Wildner

  - **All ions γ = 100**
  - **Can only store small part of the DR due to suppression of atmospheric background: SF ~ 1%**

Duty Factor = Suppression Factor



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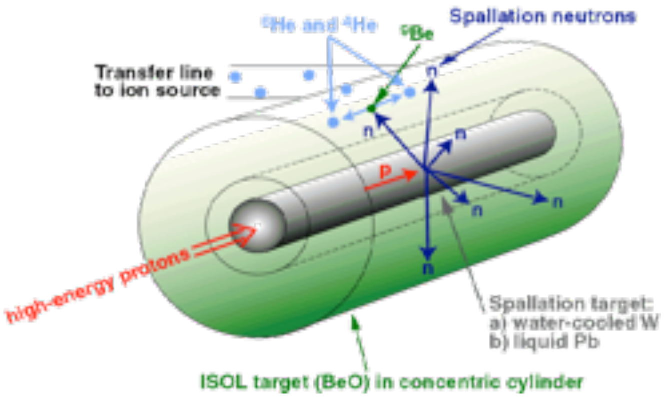
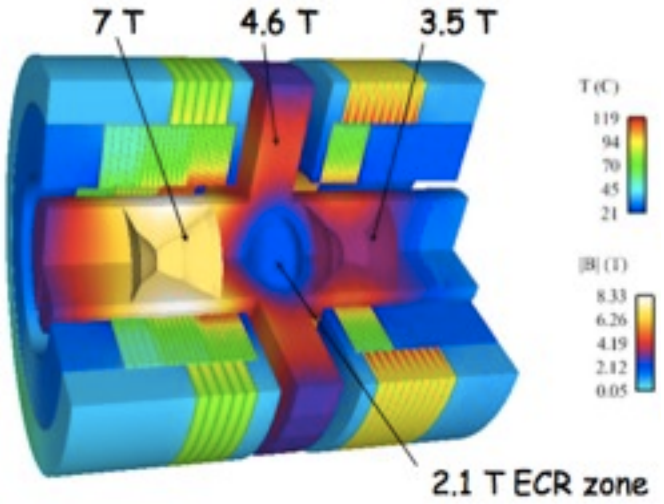
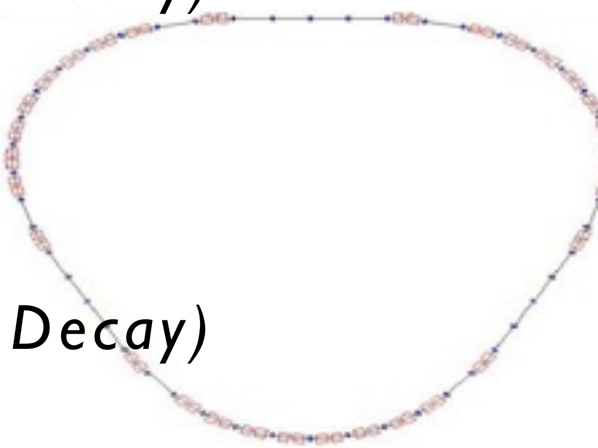
^{6}He Intensities

INTENSITIES

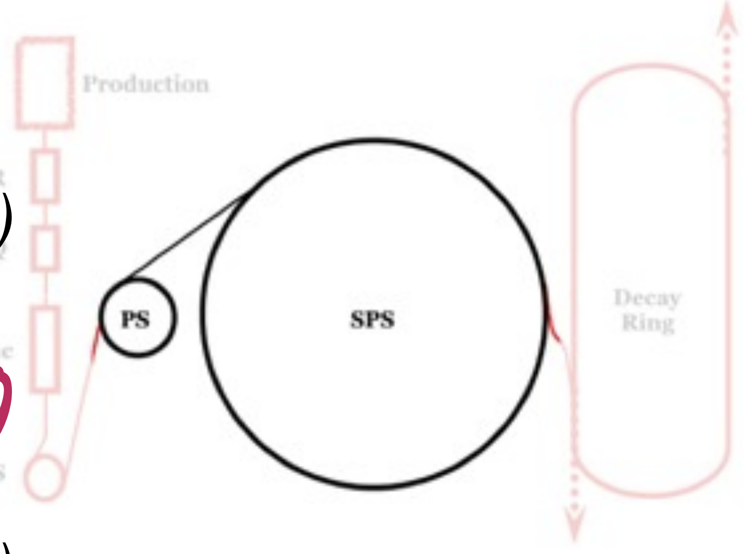




- Production
  - ➡ **5e13 ^{6}He/s**
- ECR Source (97.5 ms)
  - ➡ **1.48e13 ^{6}He/s** (**70%** *loss due to 30% eff. + Decay)*
- RCS (Bunching 5 ms and Acceleration 47.5 ms)
  - ➡ **4.66e12 ^{6}He/s** (**69%** *loss due to 50% eff. + Decay)*
- PS (Accumulation 1.9 s and Acceleration 0.8 s)
  - ➡ **2.82e12 ^{6}He/s** (**39%** *loss due to Decay)*
- SPS (Acceleration 2.5 s)
  - ➡ **1.41e12 ^{6}He/s** (**50%** *loss due to Decay)*



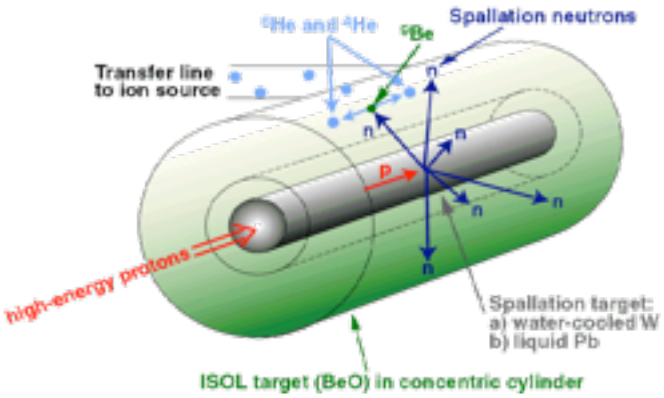
$\gamma = 100$



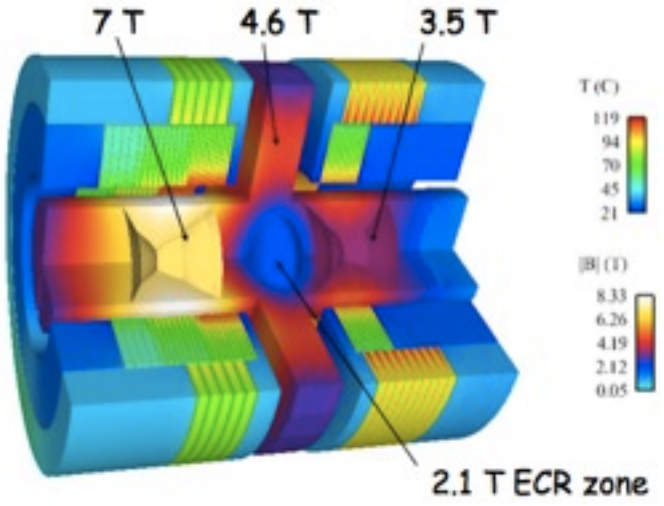
^{6}He Intensities

INTENSITIES

- Production
  - ➡ **5e13 ^{6}He/s**

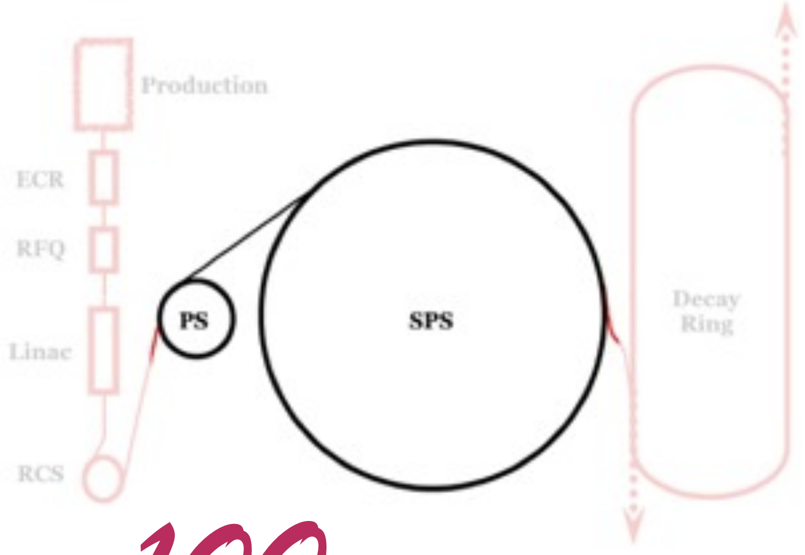


- ECR Source (1 pulse)
  - ➡ **1.44e12 ^{6}He/ECR Pulse**



- RCS (1 bunch)
  - ➡ **7.00e11 ^{6}He/bunch**

- PS (20 bunches)
  - ➡ **4.02e11 ^{6}He/bunch**
- SPS (bunches 20)
  - ➡ **3.79e11 ^{6}He/bunch**



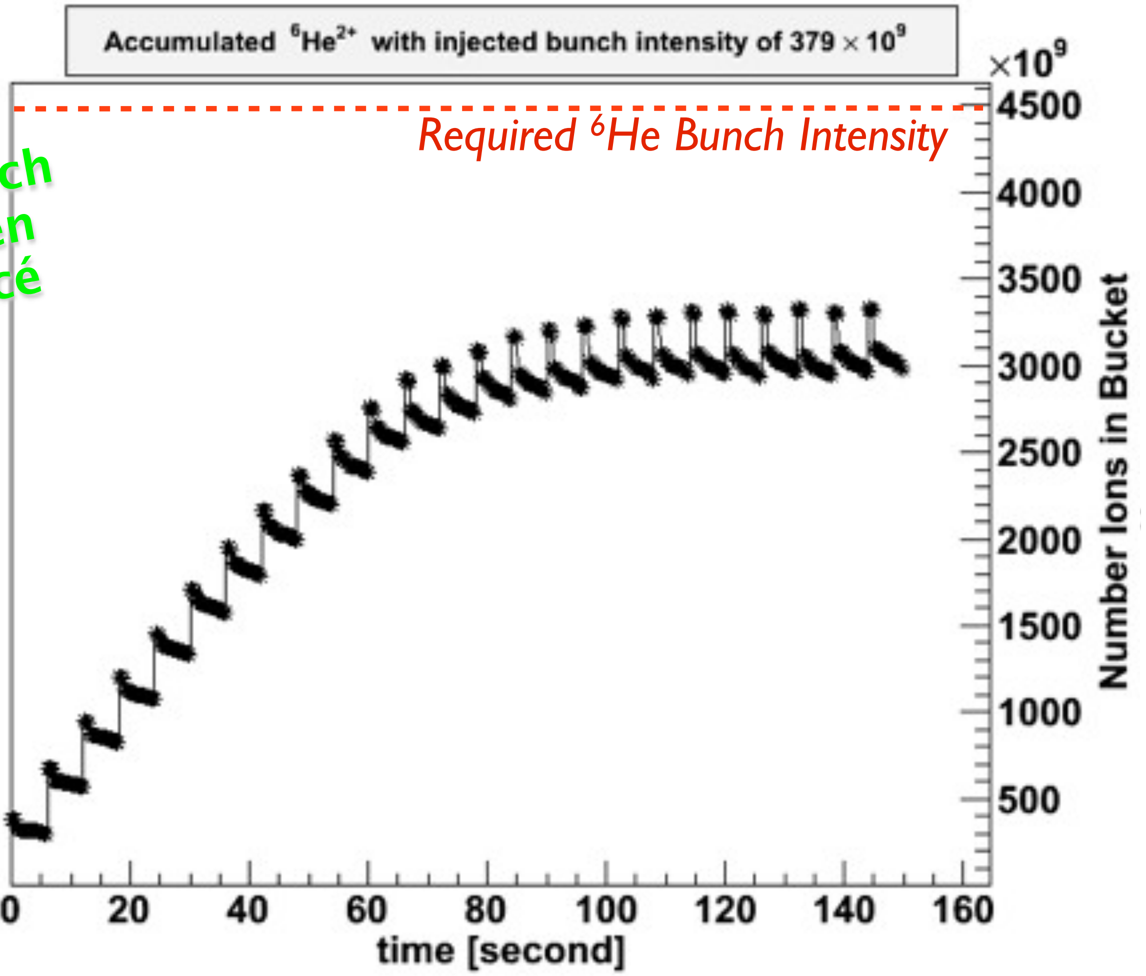
$\gamma = 100$

Previous DR Limitations

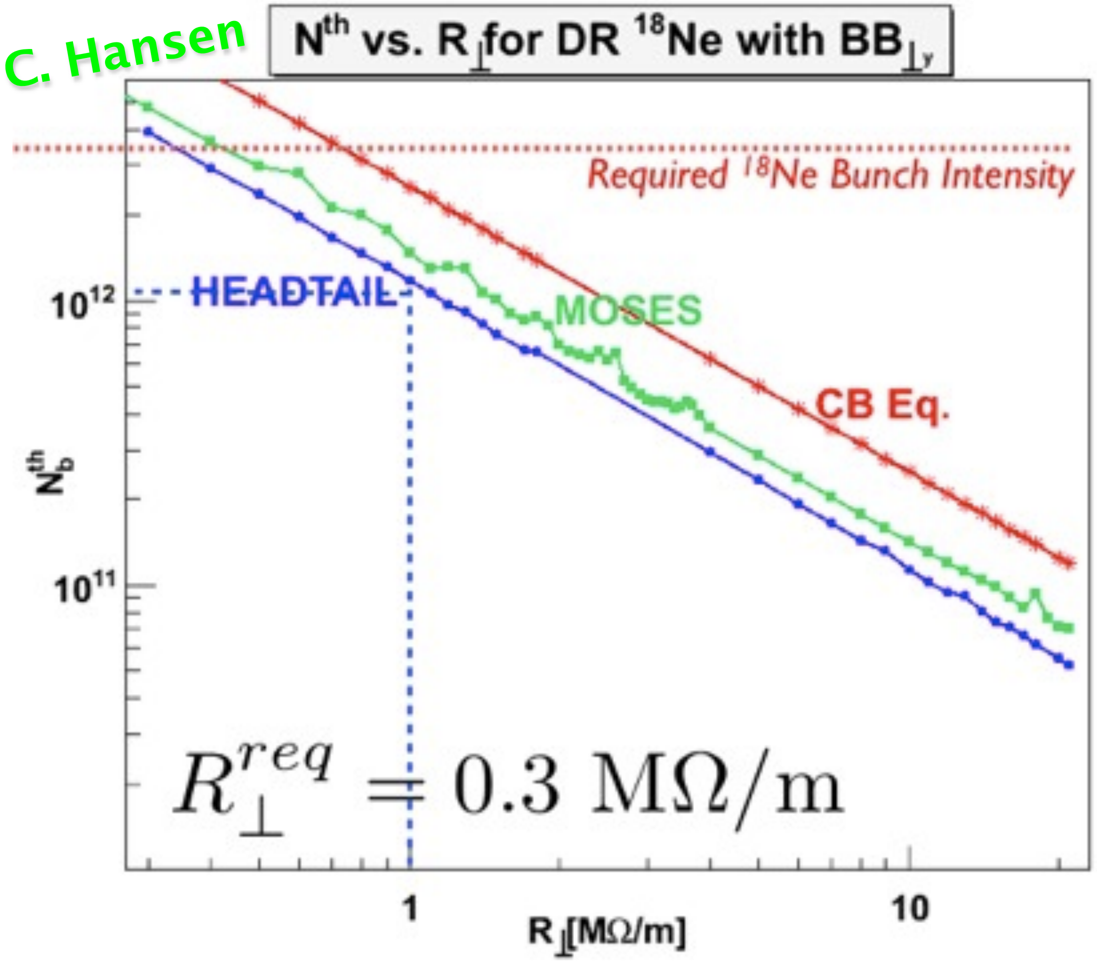
INTENSITIES

- Can the DR use these ions, **3.79e11 ^{6}He/bunch**, efficiently so we can reach enough neutrino flux?
  - ➡ <u>Before: NO!</u> Ions not only loosed by decay in the DR
  - ➡ Limited duty factor (background SF < 1%) →
    - ✦ Ions lost at collimation at the injection and
    - ✦ Ion intensities are limited due to Collective Effects

D. Heinrich
C. Hansen
A. Chancé



C. Hansen



  - ➡ Maybe not a problem anymore! What have changed??

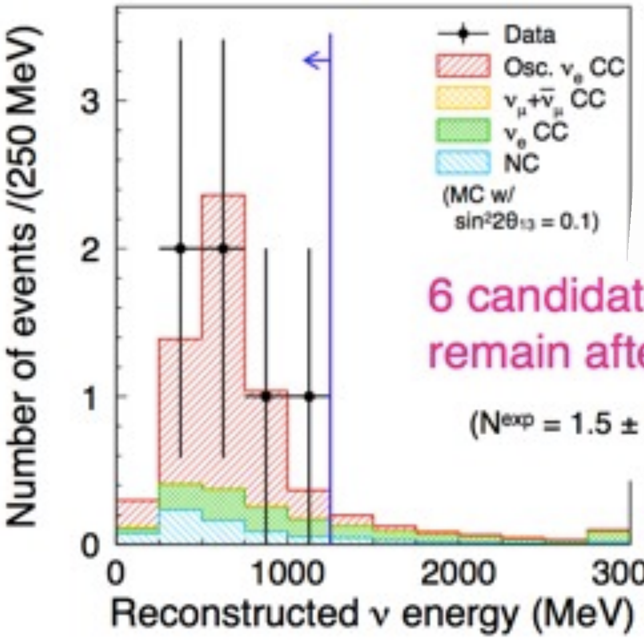
Outline

- BETA BEAMS
  - ➡ Overview
  - ➡ Beta Beam Components
  - ➡ Intensities
  - ➡ Impact of large θ_{13}
- Summary

T2K θ_{13} Indications

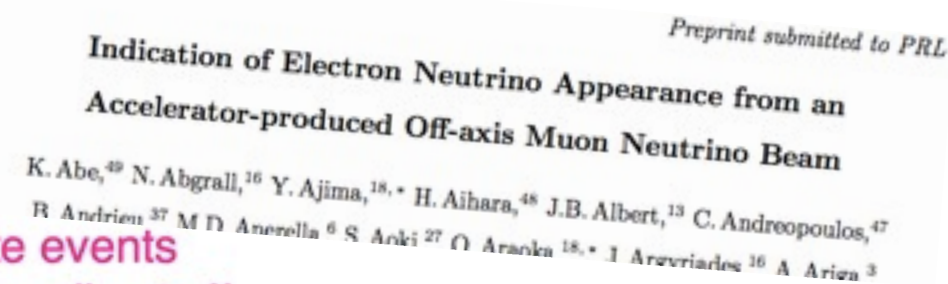
LARGE θ_{13}

- T2K indicates with 2.5σ that $\sin^2 2\theta_{13} > 0.03$ ($\Delta m_{23}^2 > 0$)



6 candidate events remain after all cuts !!

($N^{exp} = 1.5 \pm 0.3$ at $\sin^2 2\theta_{13}=0$)



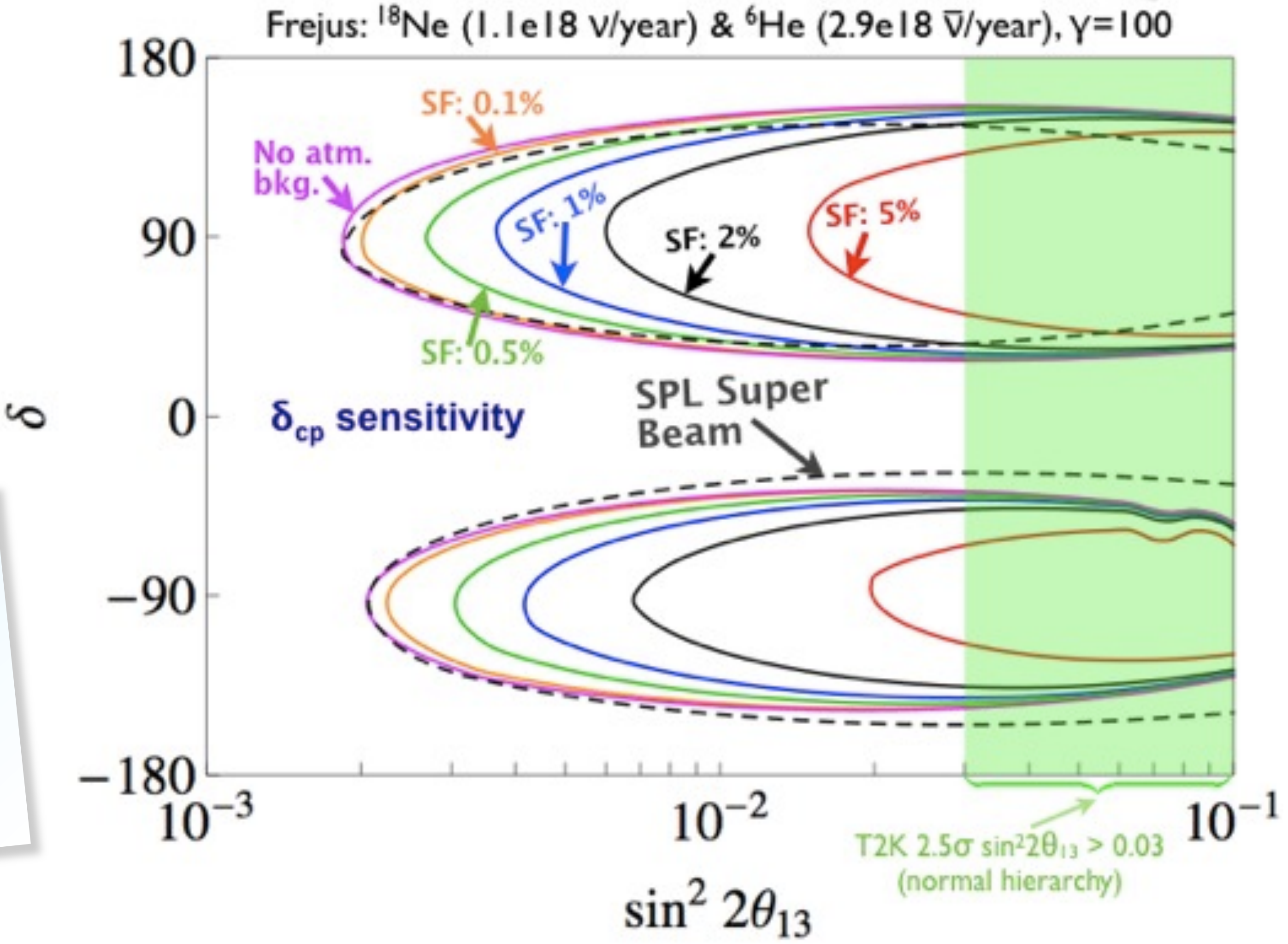
Preprint submitted to PRL

Indication of Electron Neutrino Appearance from an Accelerator-produced Off-axis Muon Neutrino Beam

K. Abe,[49] N. Abgrall,[16] Y. Ajima,[18,*] H. Aihara,[48] J.B. Albert,[13] C. Andreopoulos,[47] B. Andrieu,[37] M.D. Anerella,[6] S. Aoki,[27] O. Araoka,[18,*] J. Argyriades,[16] A. Ariga,[3]

- → SF not as crucial for Beta Beams; SF = 2% allowed! Even 2.3% … ? (before SF = 0.58%)

E. Fernandez-Martinez



Comparison with sbeam is incomplete due to unknown systematic errors (here put to 5% for signal and 10% for bkg for both βbeams and sbeams)

Large θ_{13} Impacts

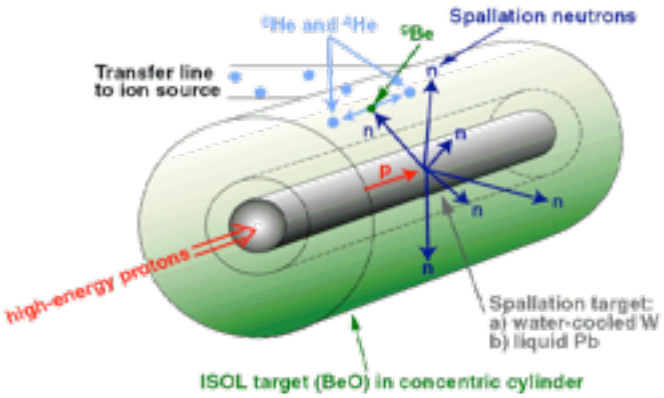
- If SF = 2.3% → 4 times more of DR can be used
- 3 ways to use this
  - 80 2m bunches in DR → SF = 2.3%
    - 4 PS batches into SPS, same DR merging
      - More decay before DR injection,
      - Same collimation
      - Less bunch intensity → less Coll. Eff.
  - 20 8m bunches in DR → SF = 2.3%
    - Same bunch scheme, but “merge” less
      - Same decay, less collimation
  - 160m long Barrier Bucket → SF = 2.3%
    - Keep all 8e13 ions in one big bunch

The efficiency has been studied (next 2 slides)

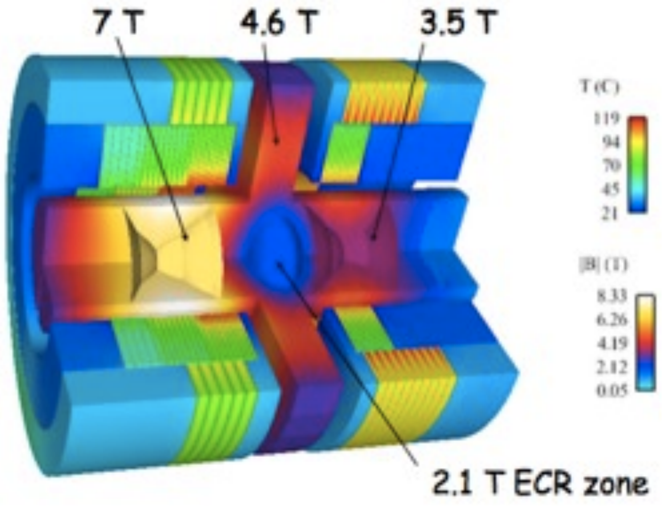
Might be better efficiency (to be studied)

^{6}He Intensities for SF 2.3%

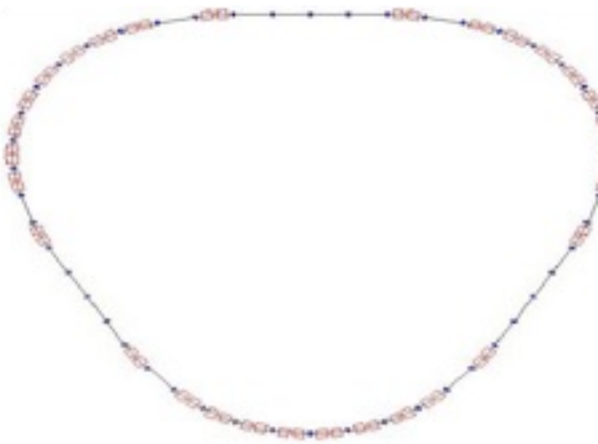
- Production
  - ➡ **5e13 ^{6}He/s**



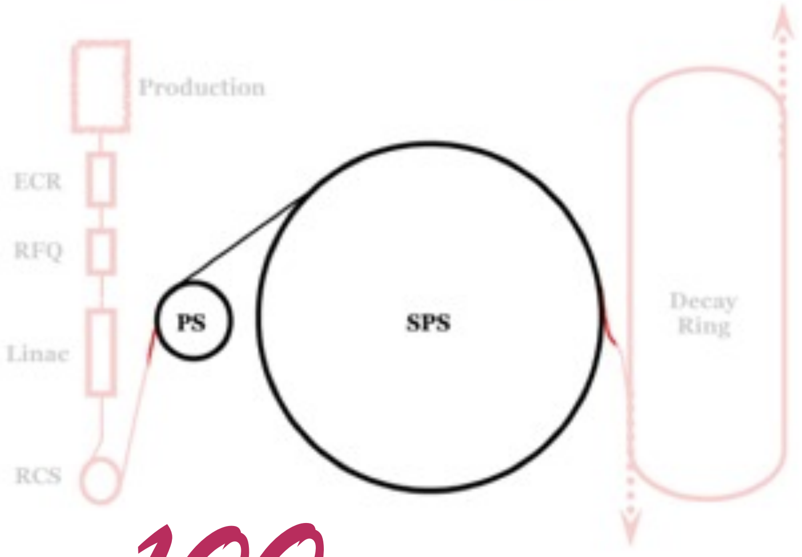
- ECR Source (pulse)
  - ➡ **1.44e12 ^{6}He/ECR Accumulation**



- RCS (1 bunch)
  - ➡ **7.00e11 ^{6}He/bunch**



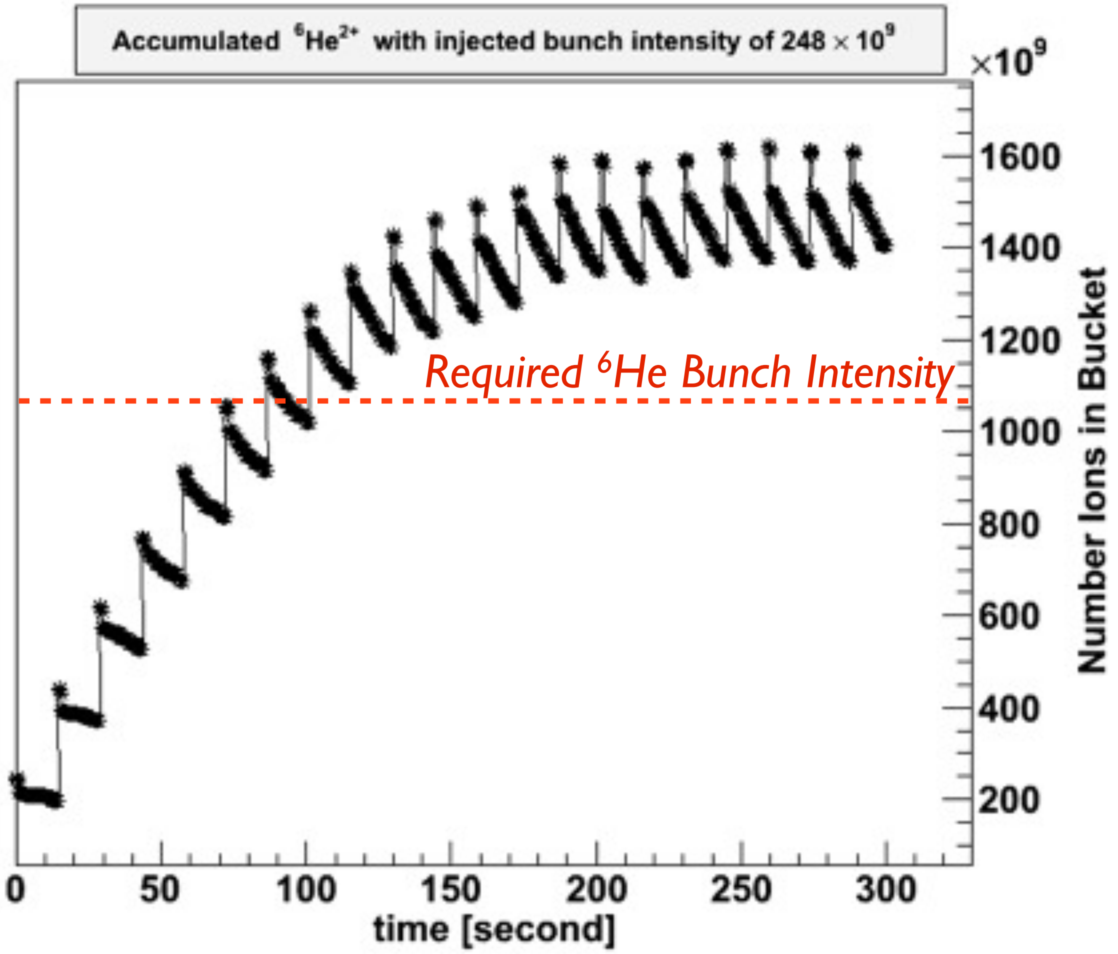
- PS (20 bunches)
  - ➡ **4.02e11 ^{6}He/bunch**
- SPS (80 bunches)
  - ➡ **2.48e11 ^{6}He/bunch**

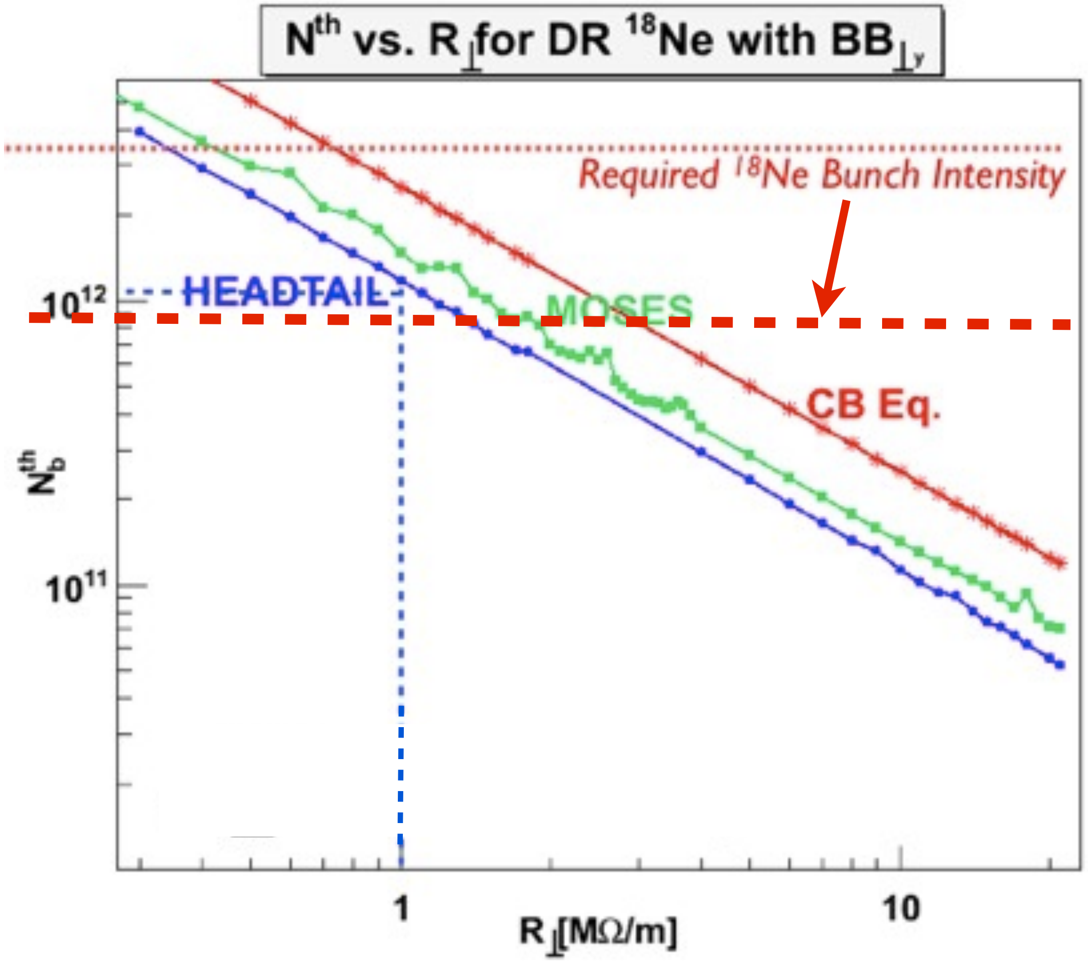


$\gamma = 100$

Solved DR Limitations

- **2.48e11 ^{6}He/bunch** enters DR in 80 bunches!
- 4 times less bunch intensity required
  - ➡ Enough intensity can be merged
  - ➡ Collective effect no longer problem (if $R_\perp^{DR}$ = 1 M/Ωm)
    - ✦ Resistive Wall and Longitudinal to be studied





Outline

- BETA BEAMS
  - Overview
  - Beta Beam Components
  - Intensities
  - Impact of large θ_{13}
- Summary

Summary

- The detailed study program for Beta Beam implementation at CERN was presented
  - ➡ Encouraging ion production progress towards required source rate
    - ✦ ^{18}Ne production experiment scheduled at CERN
  - ➡ Well established beam preparation and acceleration
    - ✦ State of the art studies for a 60GHz ECR ongoing

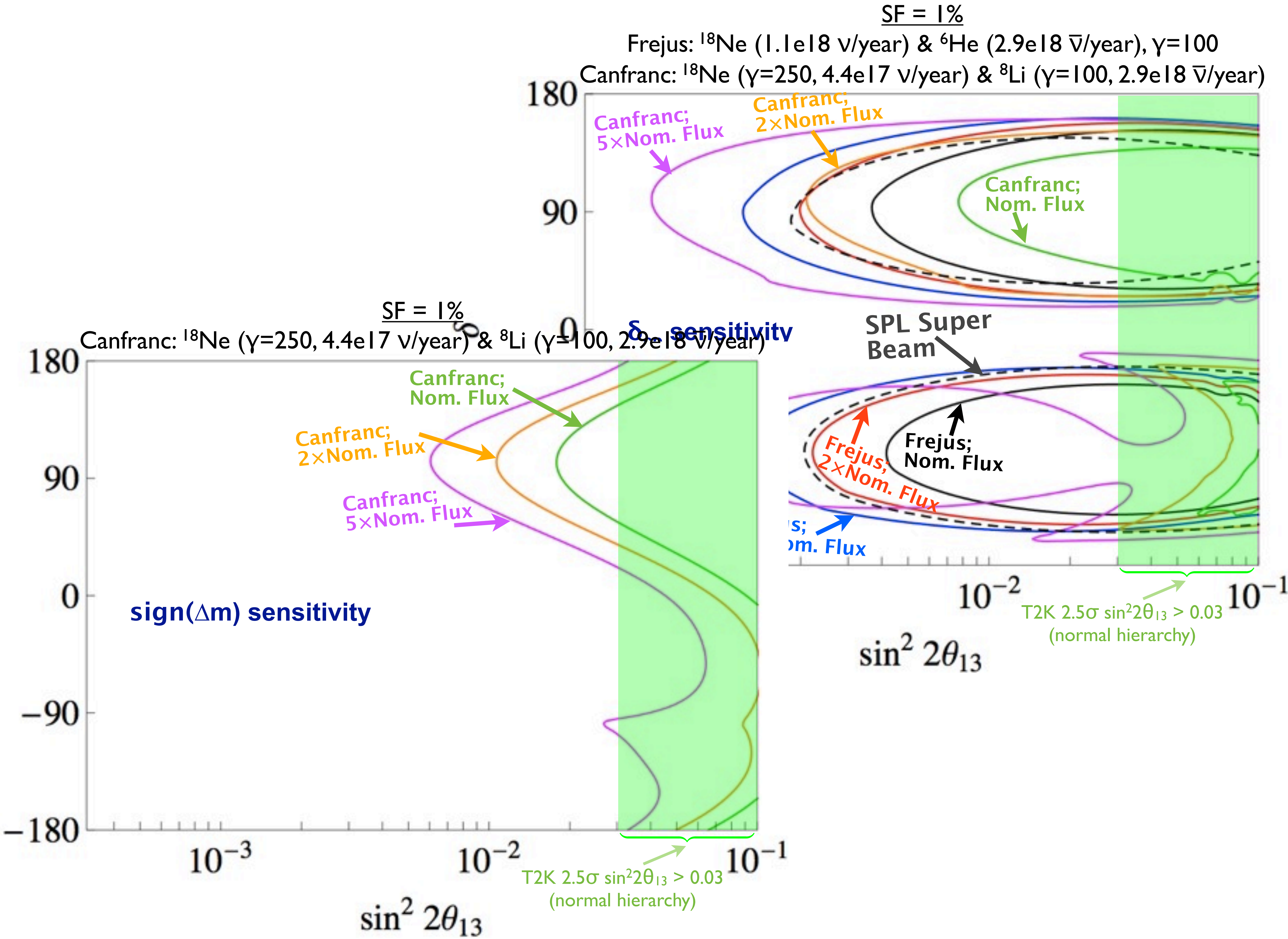
- Large θ_{13} shows prosperous possibilities for βB
  - ➡ Enough intensity can be merged and stored in the DR
    - ✦ More studies needed!

Backup Slides

Other βB Ideas

E. Fernandez-Martinez

LARGE θ_{13}



SF = 1%

Frejus: ^{18}Ne (1.1e18 ν/year) & ^{6}He (2.9e18 $\bar{\nu}$/year), γ=100

Canfranc: ^{18}Ne (γ=250, 4.4e17 ν/year) & ^{8}Li (γ=100, 2.9e18 $\bar{\nu}$/year)

δ_{CP} sensitivity

SF = 1%

Canfranc: ^{18}Ne (γ=250, 4.4e17 ν/year) & ^{8}Li (γ=100, 2.9e18 $\bar{\nu}$/year)

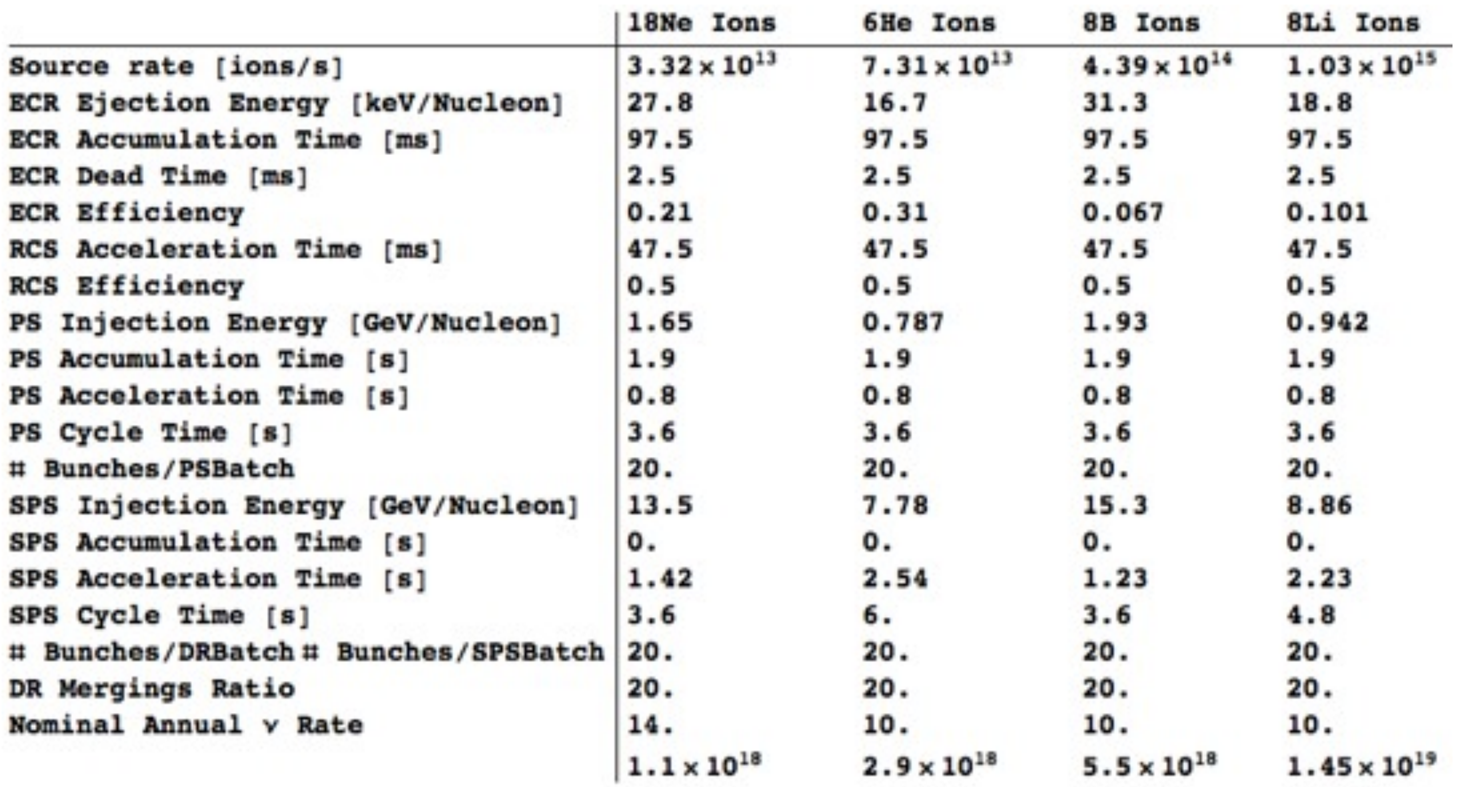
sign(Δm) sensitivity

T2K 2.5σ $\sin^2 2\theta_{13} > 0.03$ (normal hierarchy)

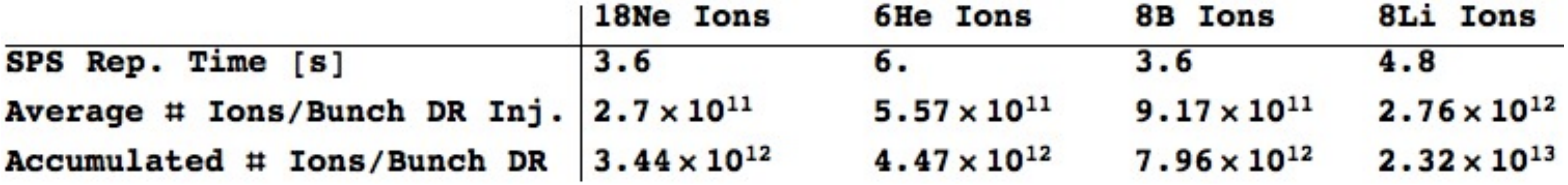
Intensities; Aimed

INTENSITIES

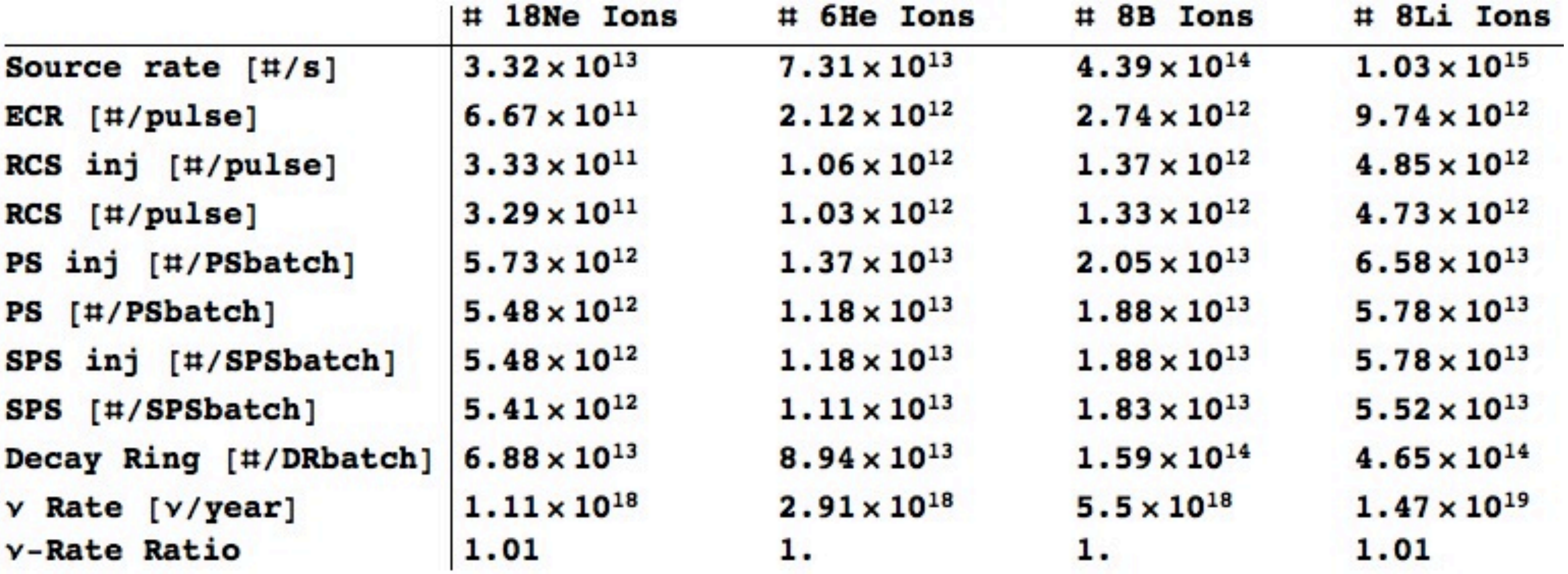
SF=0.58%



	18Ne Ions	6He Ions	8B Ions	8Li Ions
Source rate [ions/s]	3.32×10^{13}	7.31×10^{13}	4.39×10^{14}	1.03×10^{15}
ECR Ejection Energy [keV/Nucleon]	27.8	16.7	31.3	18.8
ECR Accumulation Time [ms]	97.5	97.5	97.5	97.5
ECR Dead Time [ms]	2.5	2.5	2.5	2.5
ECR Efficiency	0.21	0.31	0.067	0.101
RCS Acceleration Time [ms]	47.5	47.5	47.5	47.5
RCS Efficiency	0.5	0.5	0.5	0.5
PS Injection Energy [GeV/Nucleon]	1.65	0.787	1.93	0.942
PS Accumulation Time [s]	1.9	1.9	1.9	1.9
PS Acceleration Time [s]	0.8	0.8	0.8	0.8
PS Cycle Time [s]	3.6	3.6	3.6	3.6
# Bunches/PSBatch	20.	20.	20.	20.
SPS Injection Energy [GeV/Nucleon]	13.5	7.78	15.3	8.86
SPS Accumulation Time [s]	0.	0.	0.	0.
SPS Acceleration Time [s]	1.42	2.54	1.23	2.23
SPS Cycle Time [s]	3.6	6.	3.6	4.8
# Bunches/DRBatch # Bunches/SPSBatch	20.	20.	20.	20.
DR Mergings Ratio	20.	20.	20.	20.
Nominal Annual ν Rate	14.	10.	10.	10.
	1.1×10^{18}	2.9×10^{18}	5.5×10^{18}	1.45×10^{19}



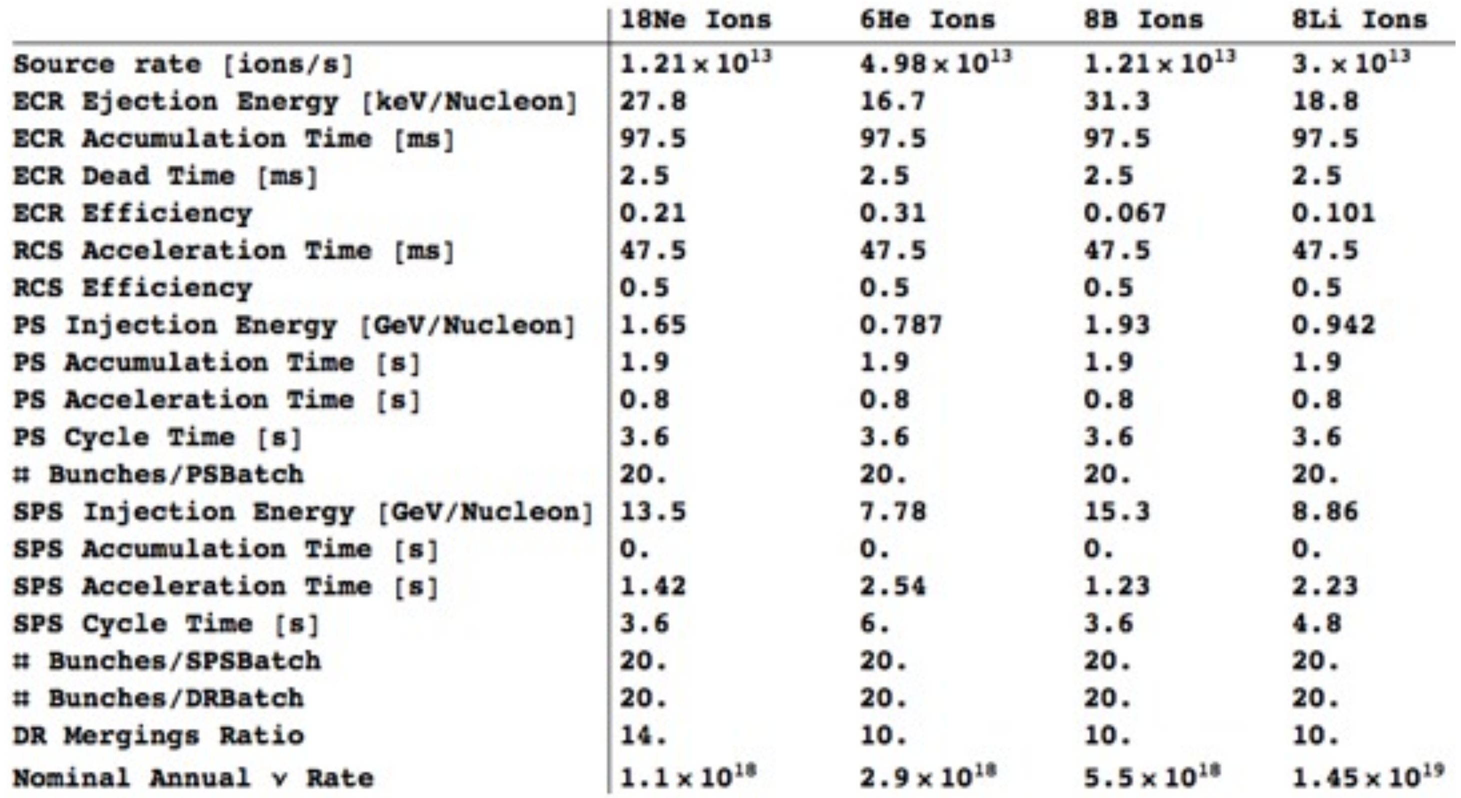
	18Ne Ions	6He Ions	8B Ions	8Li Ions
SPS Rep. Time [s]	3.6	6.	3.6	4.8
Average # Ions/Bunch DR Inj.	2.7×10^{11}	5.57×10^{11}	9.17×10^{11}	2.76×10^{12}
Accumulated # Ions/Bunch DR	3.44×10^{12}	4.47×10^{12}	7.96×10^{12}	2.32×10^{13}



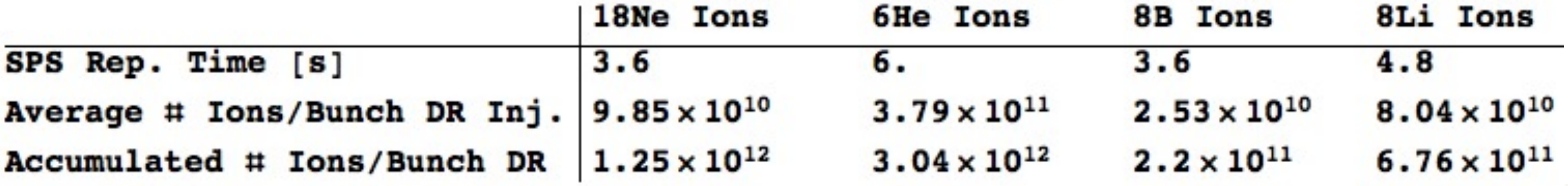
	# 18Ne Ions	# 6He Ions	# 8B Ions	# 8Li Ions
Source rate [#/s]	3.32×10^{13}	7.31×10^{13}	4.39×10^{14}	1.03×10^{15}
ECR [#/pulse]	6.67×10^{11}	2.12×10^{12}	2.74×10^{12}	9.74×10^{12}
RCS inj [#/pulse]	3.33×10^{11}	1.06×10^{12}	1.37×10^{12}	4.85×10^{12}
RCS [#/pulse]	3.29×10^{11}	1.03×10^{12}	1.33×10^{12}	4.73×10^{12}
PS inj [#/PSbatch]	5.73×10^{12}	1.37×10^{13}	2.05×10^{13}	6.58×10^{13}
PS [#/PSbatch]	5.48×10^{12}	1.18×10^{13}	1.88×10^{13}	5.78×10^{13}
SPS inj [#/SPSbatch]	5.48×10^{12}	1.18×10^{13}	1.88×10^{13}	5.78×10^{13}
SPS [#/SPSbatch]	5.41×10^{12}	1.11×10^{13}	1.83×10^{13}	5.52×10^{13}
Decay Ring [#/DRbatch]	6.88×10^{13}	8.94×10^{13}	1.59×10^{14}	4.65×10^{14}
ν Rate [ν/year]	1.11×10^{18}	2.91×10^{18}	5.5×10^{18}	1.47×10^{19}
ν-Rate Ratio	1.01	1.	1.	1.01

Intensities; Achieved

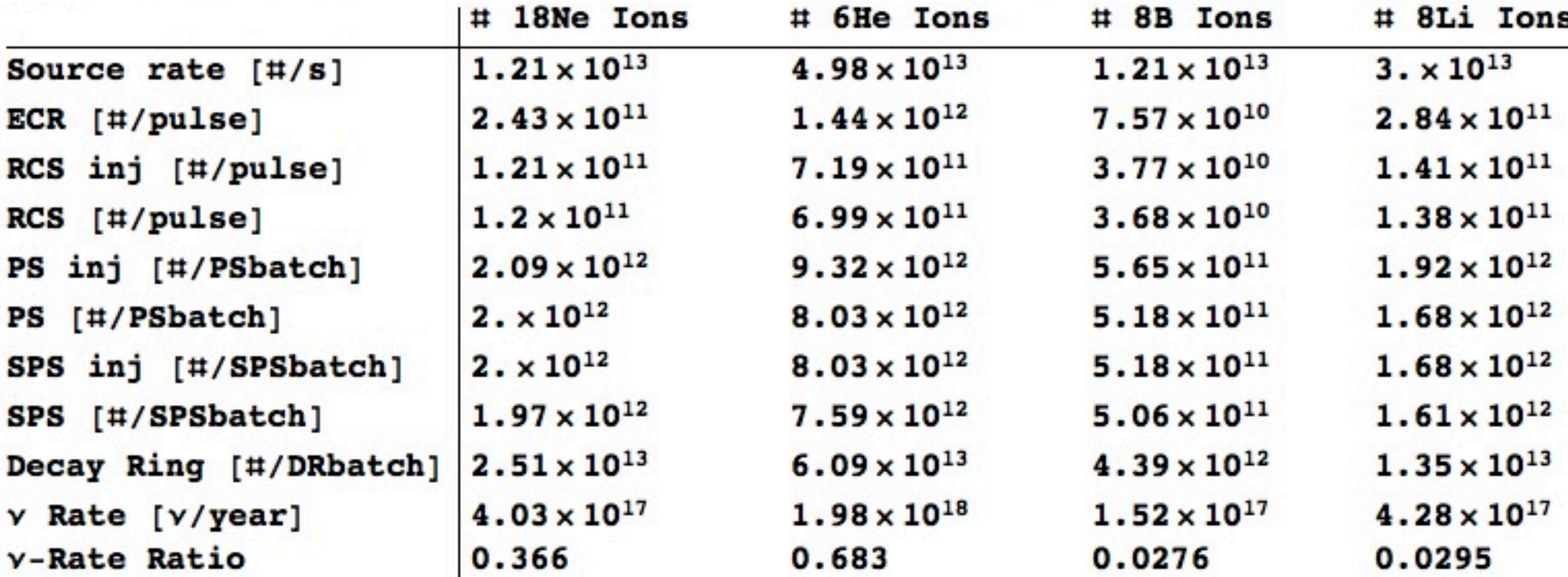
SF=0.58%



	18Ne Ions	6He Ions	8B Ions	8Li Ions
Source rate [ions/s]	1.21×10^{13}	4.98×10^{13}	1.21×10^{13}	$3.\times10^{13}$
ECR Ejection Energy [keV/Nucleon]	27.8	16.7	31.3	18.8
ECR Accumulation Time [ms]	97.5	97.5	97.5	97.5
ECR Dead Time [ms]	2.5	2.5	2.5	2.5
ECR Efficiency	0.21	0.31	0.067	0.101
RCS Acceleration Time [ms]	47.5	47.5	47.5	47.5
RCS Efficiency	0.5	0.5	0.5	0.5
PS Injection Energy [GeV/Nucleon]	1.65	0.787	1.93	0.942
PS Accumulation Time [s]	1.9	1.9	1.9	1.9
PS Acceleration Time [s]	0.8	0.8	0.8	0.8
PS Cycle Time [s]	3.6	3.6	3.6	3.6
# Bunches/PSBatch	20.	20.	20.	20.
SPS Injection Energy [GeV/Nucleon]	13.5	7.78	15.3	8.86
SPS Accumulation Time [s]	0.	0.	0.	0.
SPS Acceleration Time [s]	1.42	2.54	1.23	2.23
SPS Cycle Time [s]	3.6	6.	3.6	4.8
# Bunches/SPSBatch	20.	20.	20.	20.
# Bunches/DRBatch	20.	20.	20.	20.
DR Mergings Ratio	14.	10.	10.	10.
Nominal Annual ν Rate	1.1×10^{18}	2.9×10^{18}	5.5×10^{18}	1.45×10^{19}



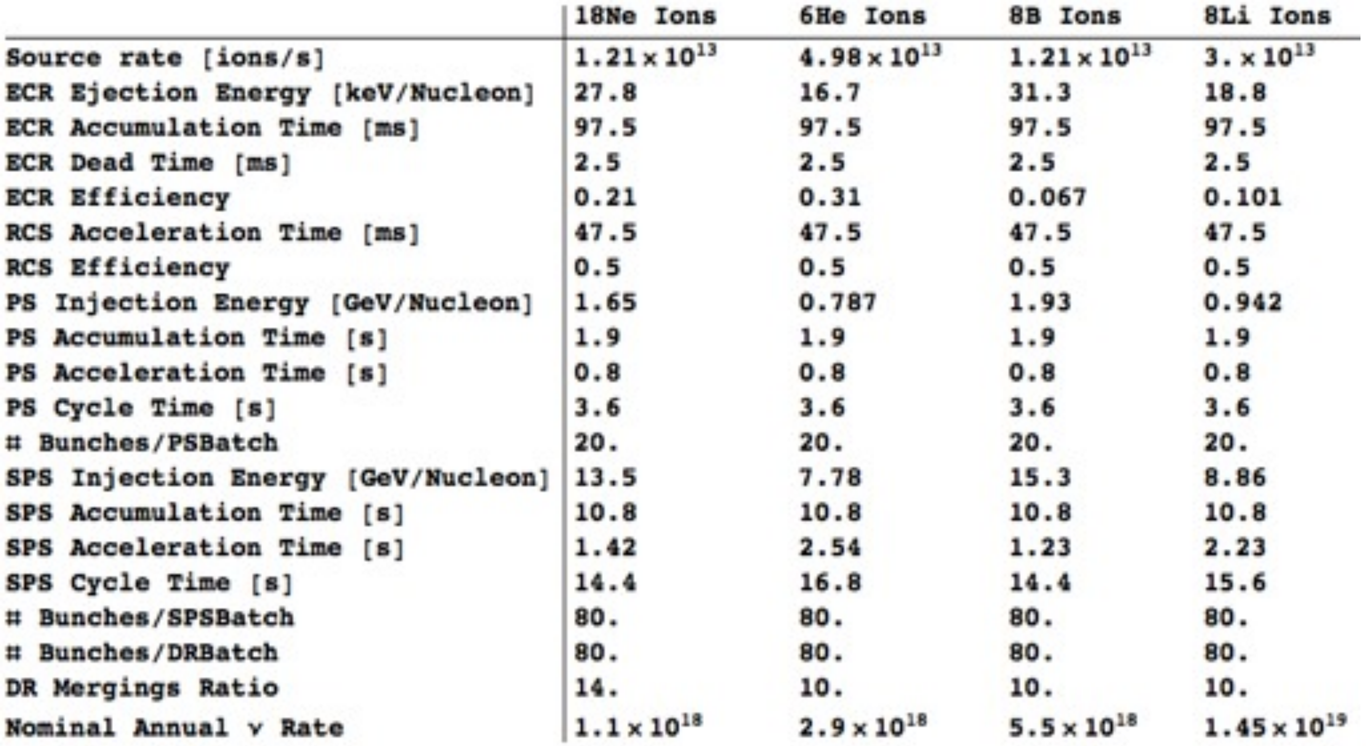
	18Ne Ions	6He Ions	8B Ions	8Li Ions
SPS Rep. Time [s]	3.6	6.	3.6	4.8
Average # Ions/Bunch DR Inj.	9.85×10^{10}	3.79×10^{11}	2.53×10^{10}	8.04×10^{10}
Accumulated # Ions/Bunch DR	1.25×10^{12}	3.04×10^{12}	2.2×10^{11}	6.76×10^{11}



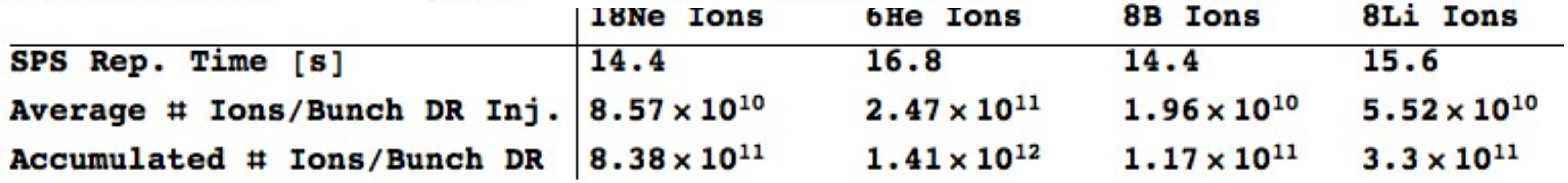
	# 18Ne Ions	# 6He Ions	# 8B Ions	# 8Li Ions
Source rate [#/s]	1.21×10^{13}	4.98×10^{13}	1.21×10^{13}	$3.\times10^{13}$
ECR [#/pulse]	2.43×10^{11}	1.44×10^{12}	7.57×10^{10}	2.84×10^{11}
RCS inj [#/pulse]	1.21×10^{11}	7.19×10^{11}	3.77×10^{10}	1.41×10^{11}
RCS [#/pulse]	1.2×10^{11}	6.99×10^{11}	3.68×10^{10}	1.38×10^{11}
PS inj [#/PSbatch]	2.09×10^{12}	9.32×10^{12}	5.65×10^{11}	1.92×10^{12}
PS [#/PSbatch]	$2.\times10^{12}$	8.03×10^{12}	5.18×10^{11}	1.68×10^{12}
SPS inj [#/SPSbatch]	$2.\times10^{12}$	8.03×10^{12}	5.18×10^{11}	1.68×10^{12}
SPS [#/SPSbatch]	1.97×10^{12}	7.59×10^{12}	5.06×10^{11}	1.61×10^{12}
Decay Ring [#/DRbatch]	2.51×10^{13}	6.09×10^{13}	4.39×10^{12}	1.35×10^{13}
ν Rate [ν/year]	4.03×10^{17}	1.98×10^{18}	1.52×10^{17}	4.28×10^{17}
ν-Rate Ratio	0.366	0.683	0.0276	0.0295

Intensities; Achieved, Large θ_{13}

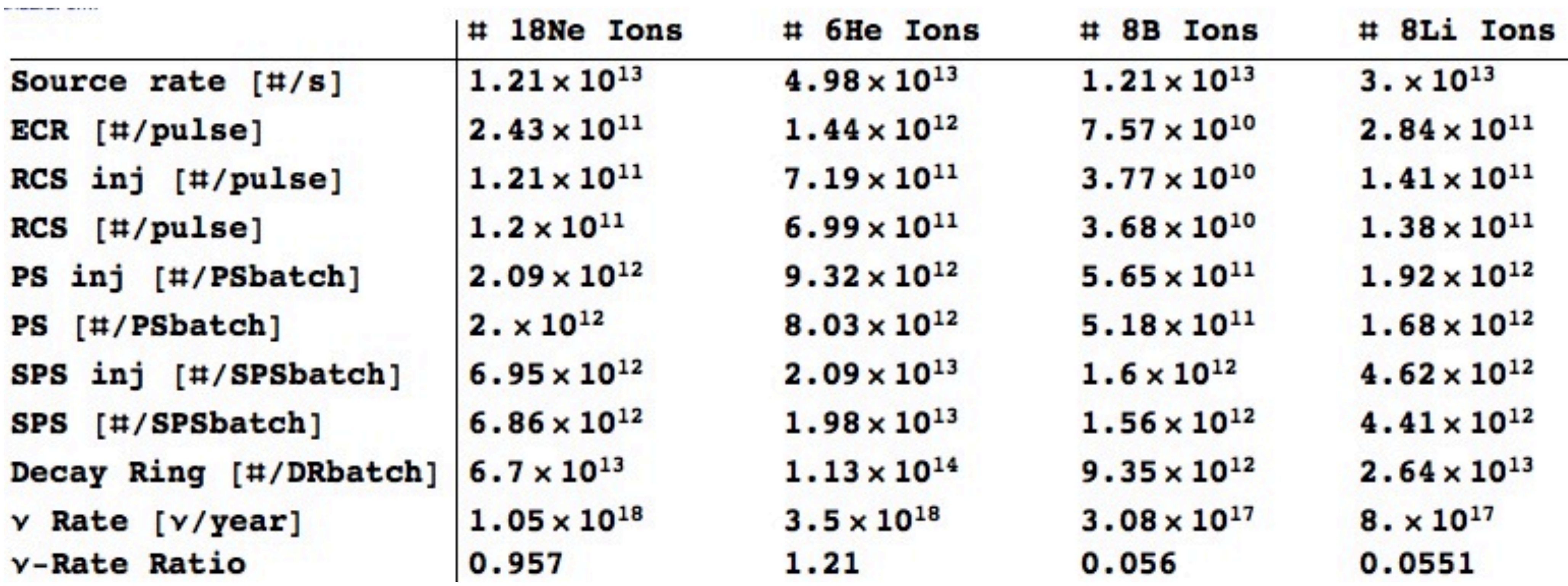
SF=2.3%



	18Ne Ions	6He Ions	8B Ions	8Li Ions
Source rate [ions/s]	1.21×10^{13}	4.98×10^{13}	1.21×10^{13}	$3.\times10^{13}$
ECR Ejection Energy [keV/Nucleon]	27.8	16.7	31.3	18.8
ECR Accumulation Time [ms]	97.5	97.5	97.5	97.5
ECR Dead Time [ms]	2.5	2.5	2.5	2.5
ECR Efficiency	0.21	0.31	0.067	0.101
RCS Acceleration Time [ms]	47.5	47.5	47.5	47.5
RCS Efficiency	0.5	0.5	0.5	0.5
PS Injection Energy [GeV/Nucleon]	1.65	0.787	1.93	0.942
PS Accumulation Time [s]	1.9	1.9	1.9	1.9
PS Acceleration Time [s]	0.8	0.8	0.8	0.8
PS Cycle Time [s]	3.6	3.6	3.6	3.6
# Bunches/PSBatch	20.	20.	20.	20.
SPS Injection Energy [GeV/Nucleon]	13.5	7.78	15.3	8.86
SPS Accumulation Time [s]	10.8	10.8	10.8	10.8
SPS Acceleration Time [s]	1.42	2.54	1.23	2.23
SPS Cycle Time [s]	14.4	16.8	14.4	15.6
# Bunches/SPSBatch	80.	80.	80.	80.
# Bunches/DRBatch	80.	80.	80.	80.
DR Mergings Ratio	14.	10.	10.	10.
Nominal Annual ν Rate	1.1×10^{18}	2.9×10^{18}	5.5×10^{18}	1.45×10^{19}



	18Ne Ions	6He Ions	8B Ions	8Li Ions
SPS Rep. Time [s]	14.4	16.8	14.4	15.6
Average # Ions/Bunch DR Inj.	8.57×10^{10}	2.47×10^{11}	1.96×10^{10}	5.52×10^{10}
Accumulated # Ions/Bunch DR	8.38×10^{11}	1.41×10^{12}	1.17×10^{11}	3.3×10^{11}



	# 18Ne Ions	# 6He Ions	# 8B Ions	# 8Li Ions
Source rate [#/s]	1.21×10^{13}	4.98×10^{13}	1.21×10^{13}	$3.\times10^{13}$
ECR [#/pulse]	2.43×10^{11}	1.44×10^{12}	7.57×10^{10}	2.84×10^{11}
RCS inj [#/pulse]	1.21×10^{11}	7.19×10^{11}	3.77×10^{10}	1.41×10^{11}
RCS [#/pulse]	1.2×10^{11}	6.99×10^{11}	3.68×10^{10}	1.38×10^{11}
PS inj [#/PSbatch]	2.09×10^{12}	9.32×10^{12}	5.65×10^{11}	1.92×10^{12}
PS [#/PSbatch]	$2.\times10^{12}$	8.03×10^{12}	5.18×10^{11}	1.68×10^{12}
SPS inj [#/SPSbatch]	6.95×10^{12}	2.09×10^{13}	1.6×10^{12}	4.62×10^{12}
SPS [#/SPSbatch]	6.86×10^{12}	1.98×10^{13}	1.56×10^{12}	4.41×10^{12}
Decay Ring [#/DRbatch]	6.7×10^{13}	1.13×10^{14}	9.35×10^{12}	2.64×10^{13}
ν Rate [ν/year]	1.05×10^{18}	3.5×10^{18}	3.08×10^{17}	$8.\times10^{17}$
ν-Rate Ratio	0.957	1.21	0.056	0.0551

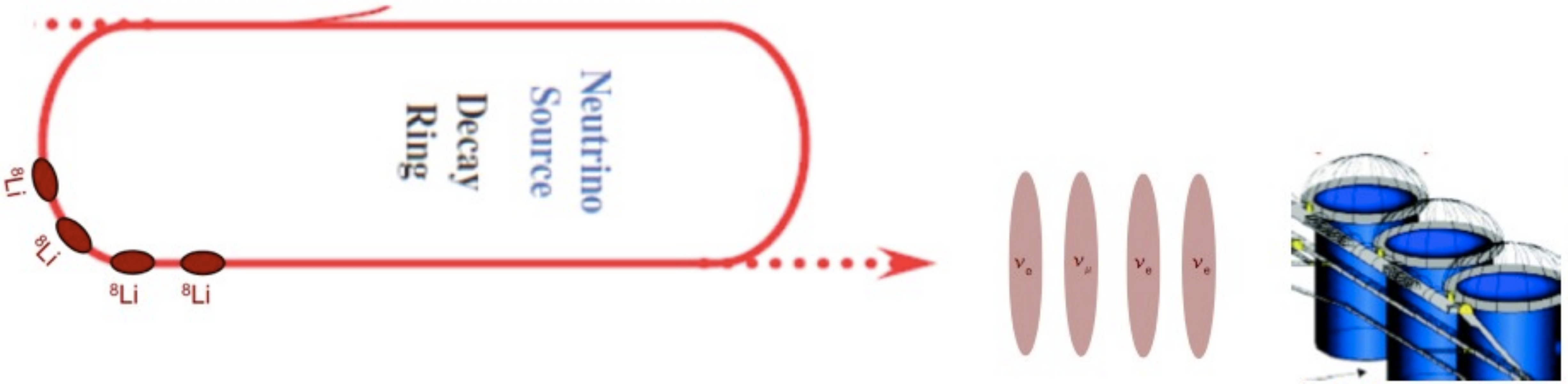
Large θ_{13} Impacts

- If SF = 2% almost 4 times (!) longer DR bunches
  - Less ion loss at collimation at DR injection
  - Less restrictions due to Collective Effects
- Might now achieve nominal fluxes! Studies needed:
  - Re-optimize bunch structure in the whole Beta Beam accelerator chain
    - Previous structure aimed at as short bunches in DR as possible
  - Re-simulate DR injection
    - capturing, merging and relaxed collimation
  - Re-simulate Collective Effects
    - 4 times longer bunches might allow 4 times more ions

DR: Duty Factor

- **To suppress atmospheric background detectors needs**
  - **Suppression Factor, SF = opened time ratio of the detector**
- **The DR will be filled only with short bunches**
  - **Duty Factor, DF = filled ratio of the Decay Ring**

Duty Factor = Suppression Factor



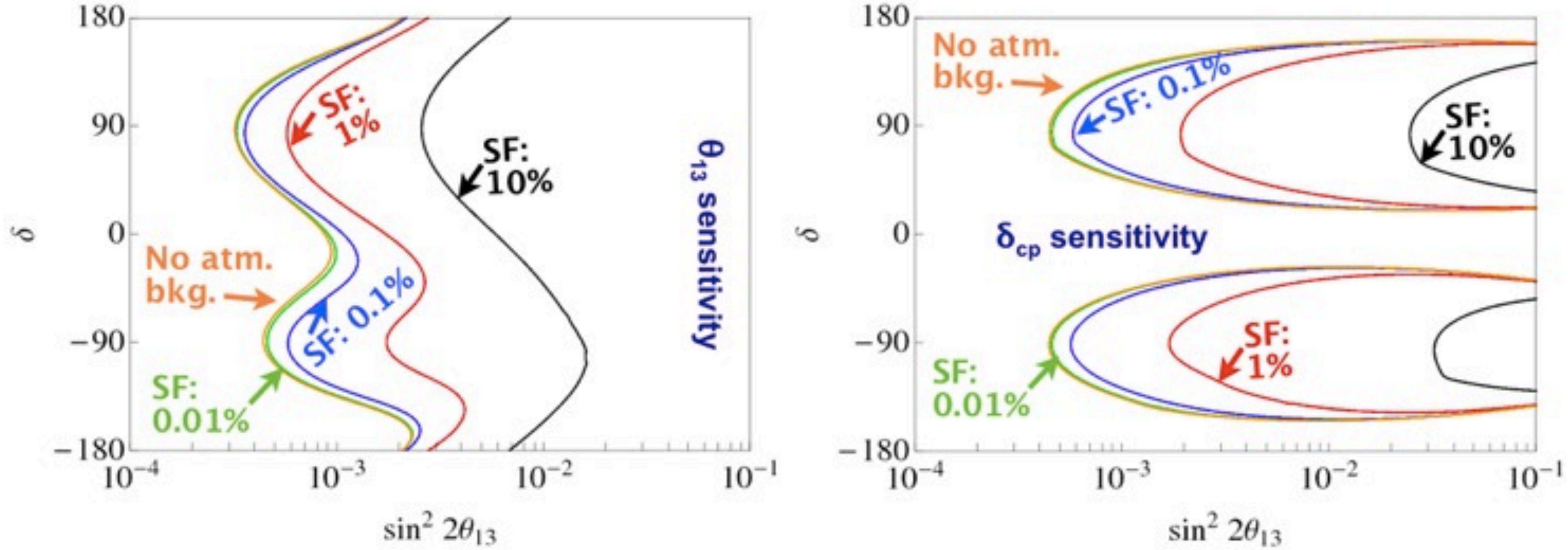
Only “opened” when neutrinos arrive

BB COMPONENTS

Aimed Sensitivities (low Q)

- Beta Beam's sensitivities depends on
  - ➡ Neutrino Fluxes (= ion intensity in DR)
  - ➡ Suppression Factor (= duty factor in DR)
- Assuming ***1.1e18 ν/year*** *from* ^{18}Ne *and* ***2.9e18 anti-ν/year*** *from* ^{6}He, we get

Assumed Fluxes: 1.1e18 ν/year from ^{18}Ne and 2.9e18 anti-ν/year from ^{6}He



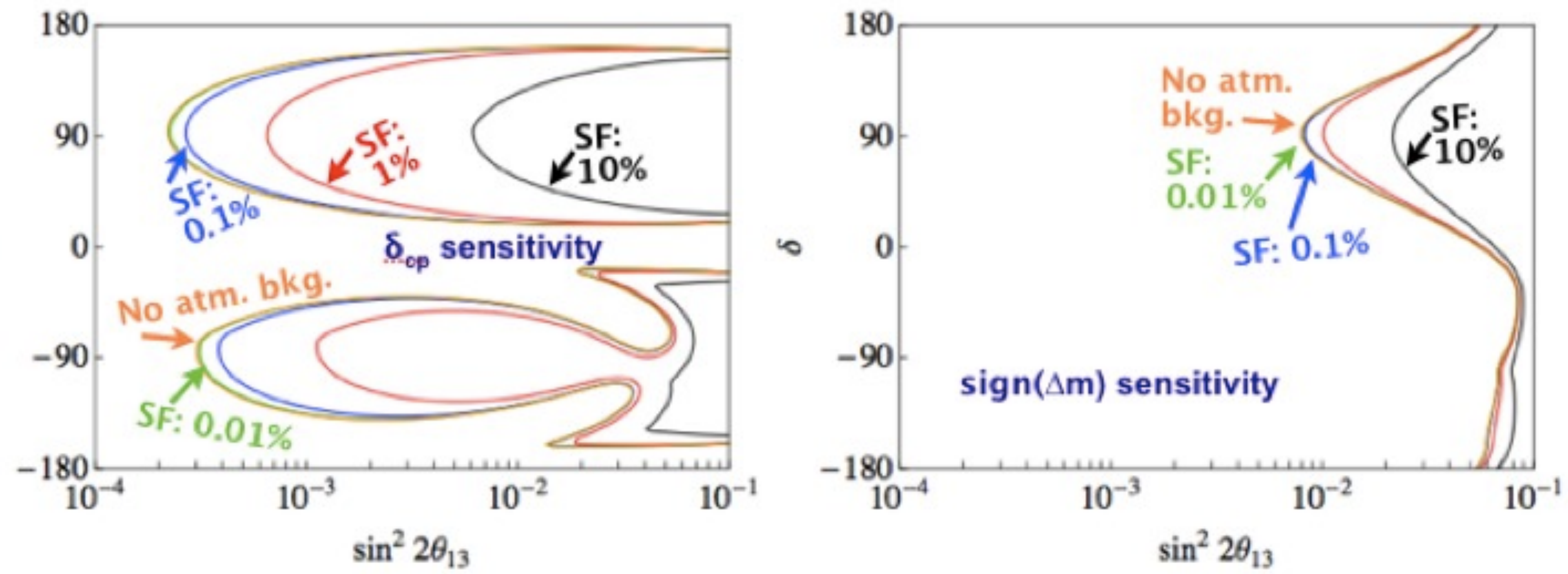
E. Fernandez, The gamma = 100 Beta-Beam Revisited. Nucl. Phys., B833:96-107,2010, 0912.3804

- I.e. with this flux we'll fill ~1% of the DR
- 20 bunches → Bunch Length ≈ 2m

Aimed Sensitivities (high Q)

- Longer baseline, different cross-section, and more gives that required ν-intensities are 5 times more
- Assuming ***5.5e18 ν/year*** *from* ^{8}*B and* ***1.5e19 anti-ν/year*** *from* ^{8}*Li*, we get

Assumed Fluxes: 5.5e18 ν/year from ^{8}B and 1.45e19 anti-ν/year from ^{8}Li



E. Fernandez, The gamma = 100 Beta-Beam Revisited. Nucl. Phys., B833:96-107,2010, 0912.3804

- I.e. also for high-Q bunch length ≈ 2m (SF ~1%)

How to Reach Aimed Sensitivities

- Aimed Fluxes:
  - ***1.1e18 ν/year*** *from* ^{18}*Ne and*
    2.9e18 anti-ν/year *from* ^{6}*He*
  - ***5.5e18 ν/year*** *from* ^{8}*B and*
    1.5e19 anti-ν/year *from* ^{8}*Li*
    - Need:
      High Ion Production Rate
      Fast Acceleration
      High Transmission Efficiency
- Aimed Duty Factor
  - Fill only 1% of the DR, i.e. bunch length ~2m
    - Merging

RFQ and Linac

- **From ECR: stripped ions** with 8 keV/u
  - **dc pulses → bunched with Linac's RF**

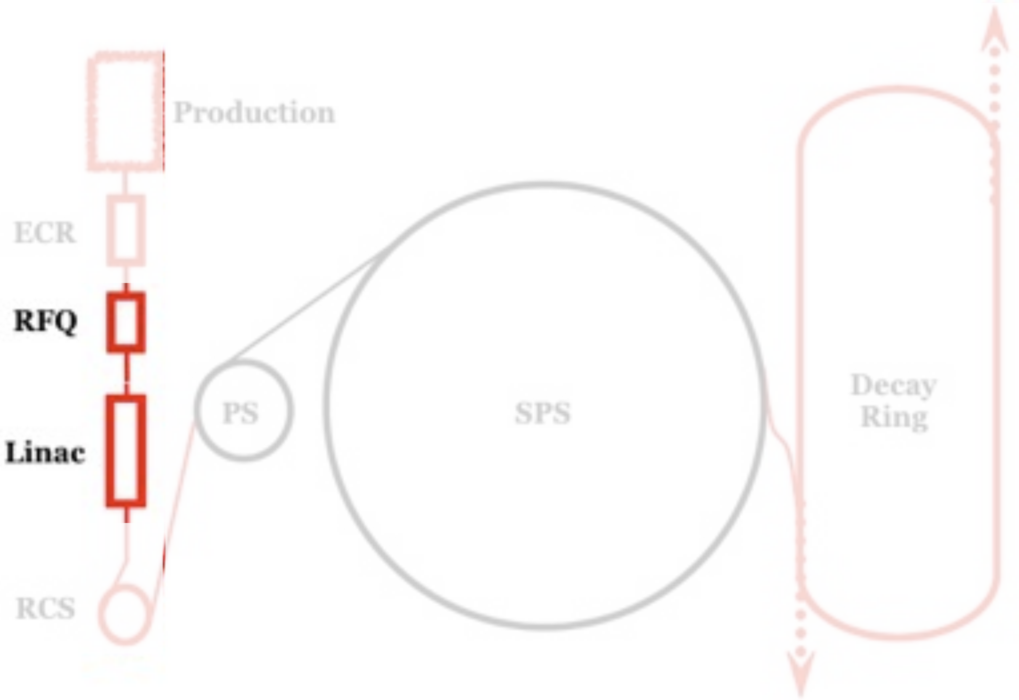
- **RFQ: Radio Frequency Quadropole**
  - **Pre-acceleration**

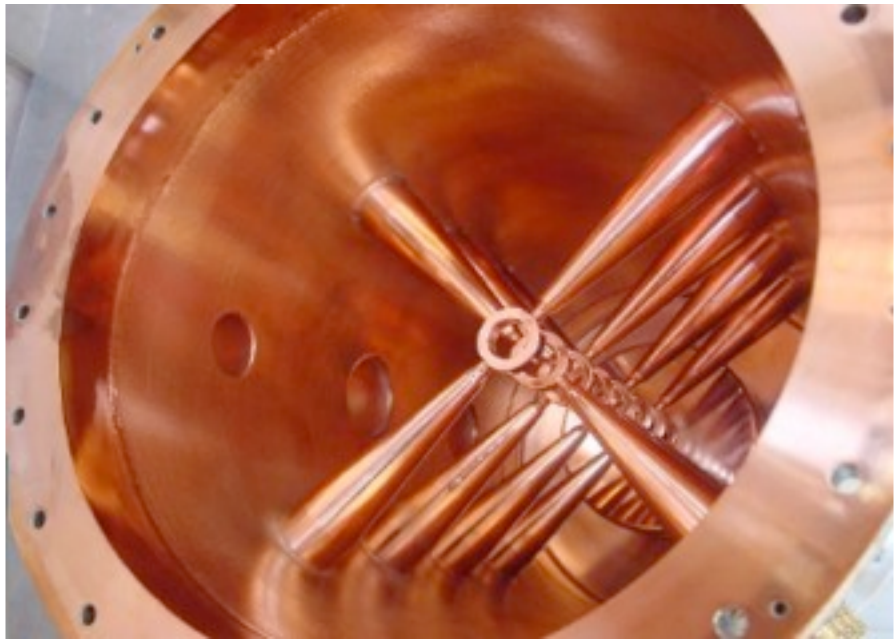
- **Conventional Linear Accelerator**
  - **normal RF cavities**
  - **bunching the dc pulses**
  - **accelerating gradient 3 – 6 MV/m**

  - **accelerate to 100 MeV/u; at ejection**

→ $B\rho = p/eZ = 2.66$ Tm (^{18}Ne) & 4.44 Tm (^{6}He)

→ $E_{tot} = 18.6$ GeV (^{18}Ne) & 6.21 GeV (^{6}He)



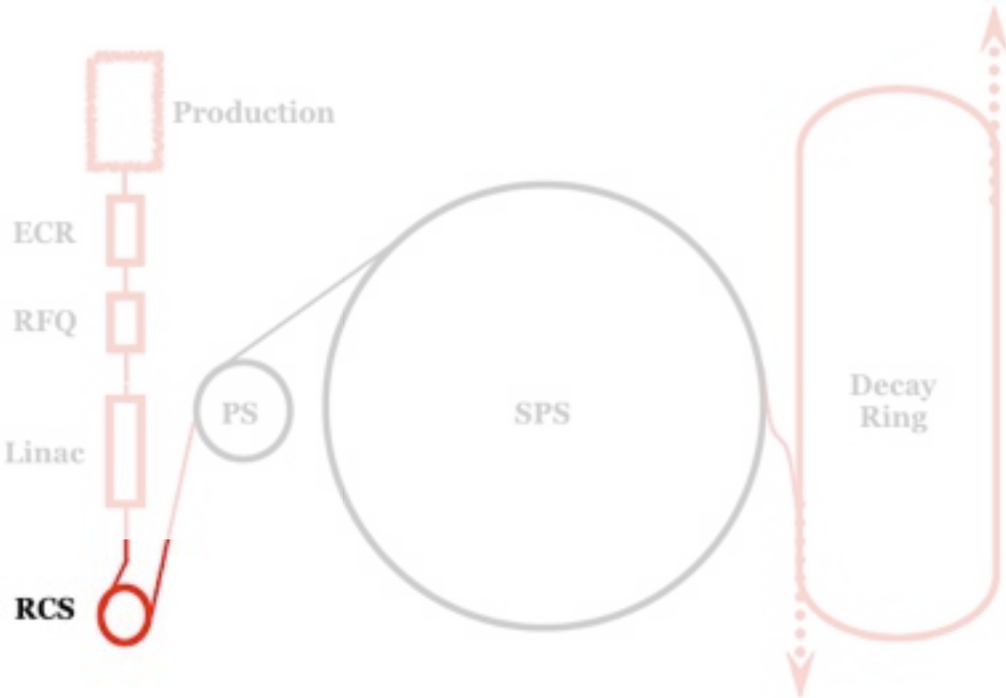


RCS - Rapid Cycling Synchrotron

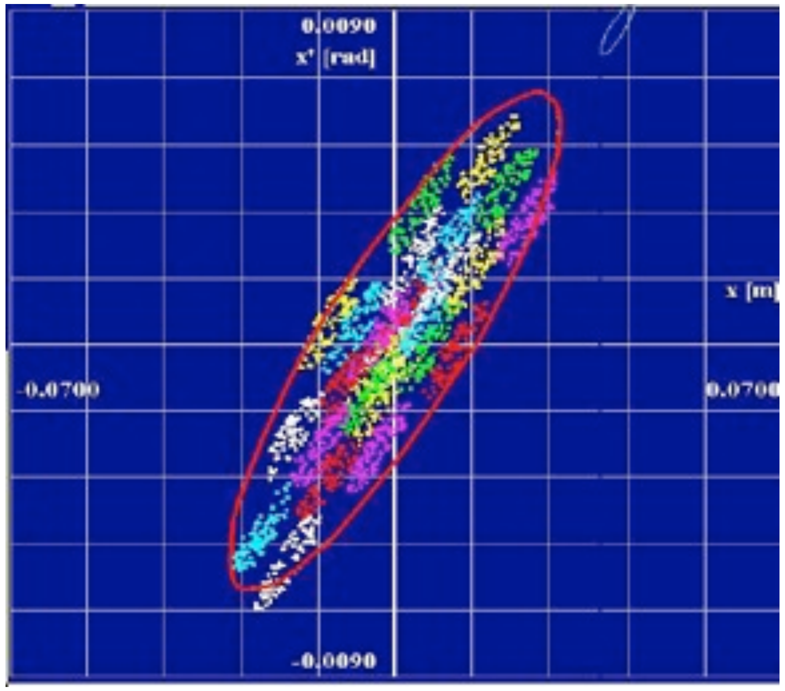
A. Lachaize

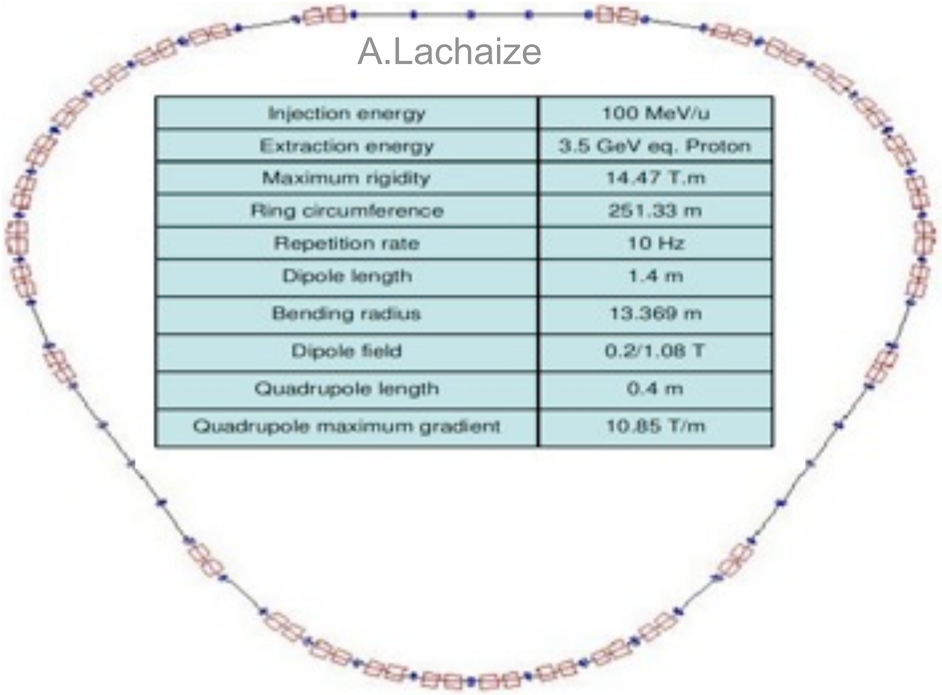
- **Multiturn Injection**
  - Pulses = 50 μs
  - RCS rev. time = 1.96 μs

  } 26 turns for injection
  - Aim: maximize # ions in required emittance
  - Method: rotation in x-x' space before next injection
  - RF: optimized to fit 26 injections
  - Result: injection efficiency 80%



- **Acceleration**
  - to 14.47 Tm

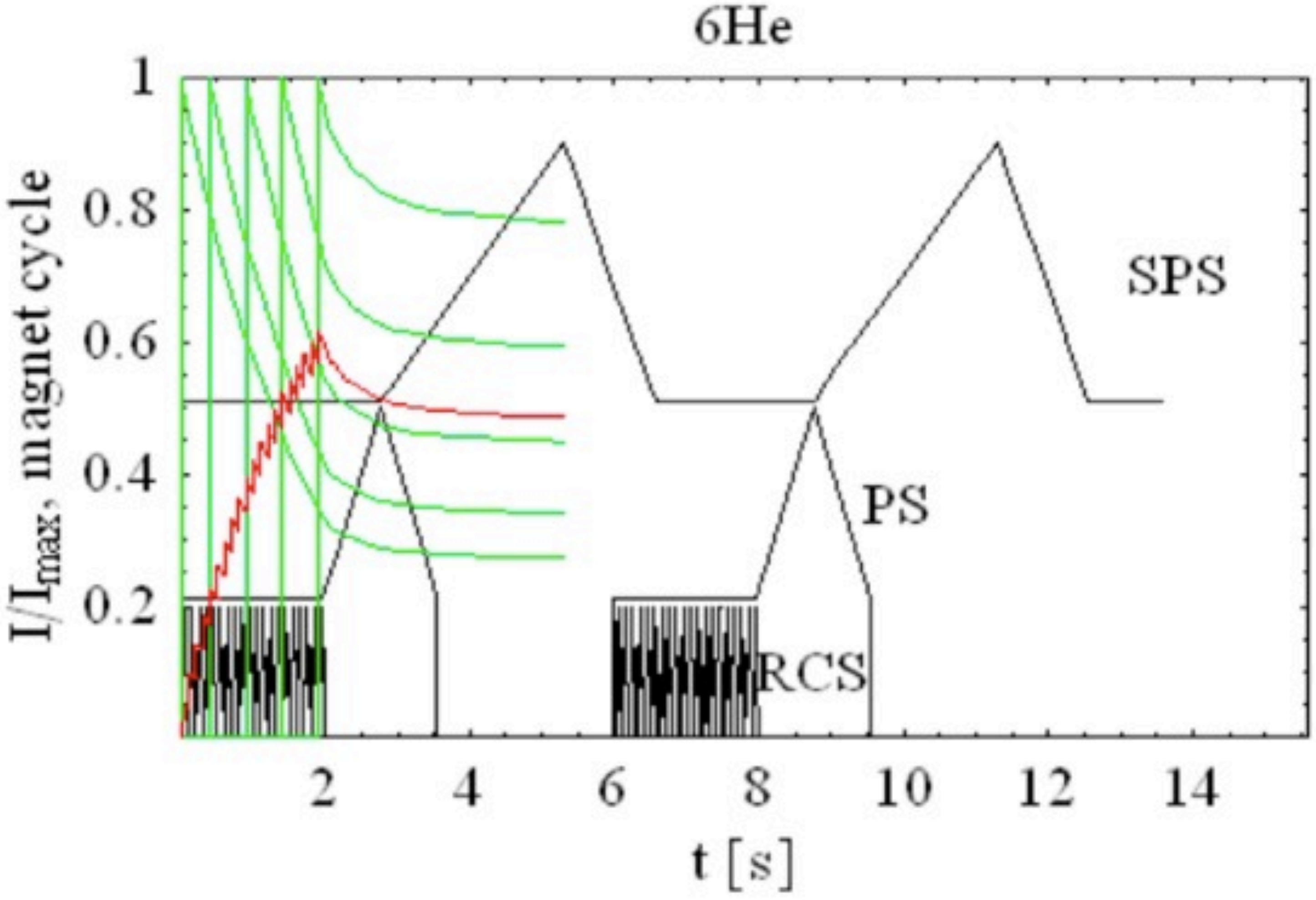


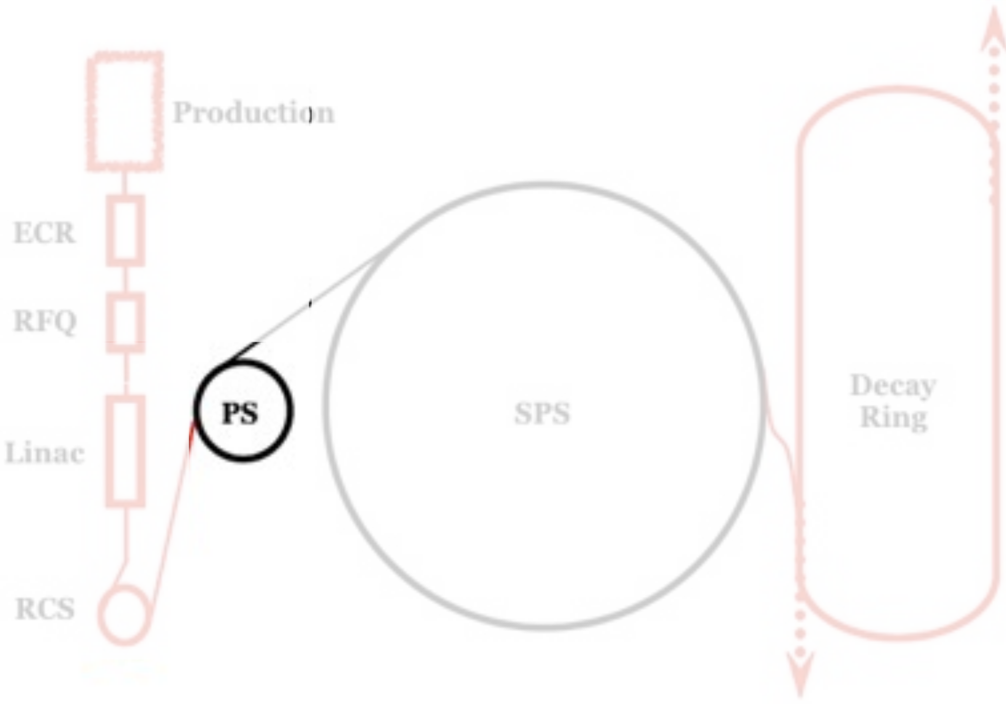

A.Lachaize

Injection energy	100 MeV/u
Extraction energy	3.5 GeV eq. Proton
Maximum rigidity	14.47 T.m
Ring circumference	251.33 m
Repetition rate	10 Hz
Dipole length	1.4 m
Bending radius	13.369 m
Dipole field	0.2/1.08 T
Quadrupole length	0.4 m
Quadrupole maximum gradient	10.85 T/m

PS - Proton Synchrotron

- **PS (h=21) Accumulation**
  - **20 injections one by one**
  - **1.9 s between first and last bunch → bunch-intensities differs due to decay**

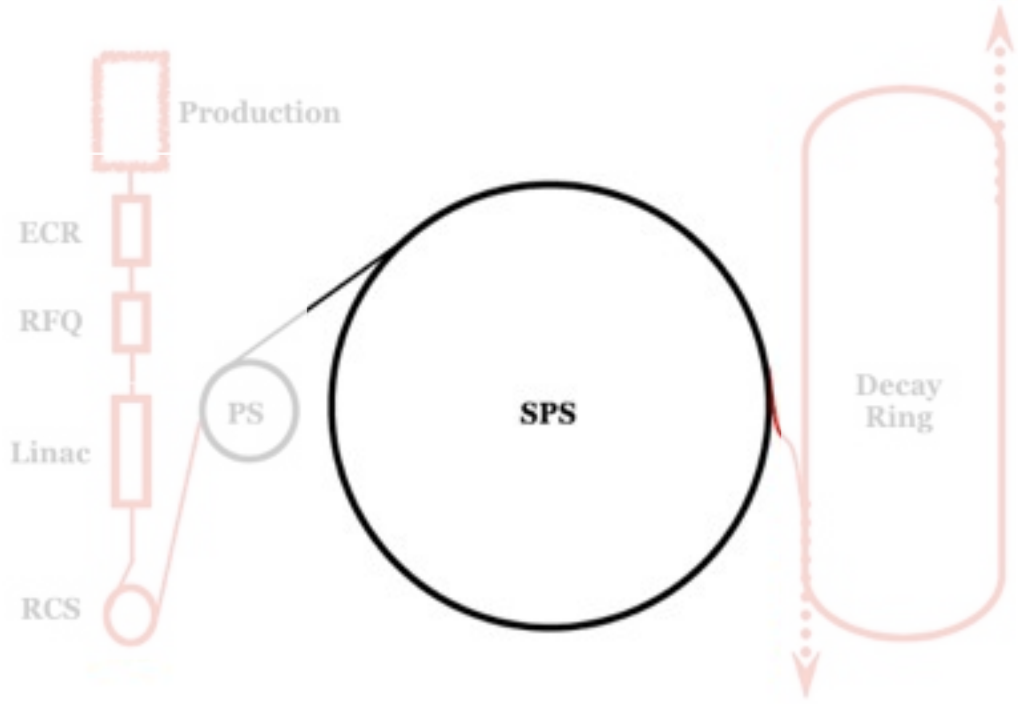




- **PS Acceleration**
  - **to 86.7 Tm** (PS max)

SPS (+) - Super Proton Synchrotron

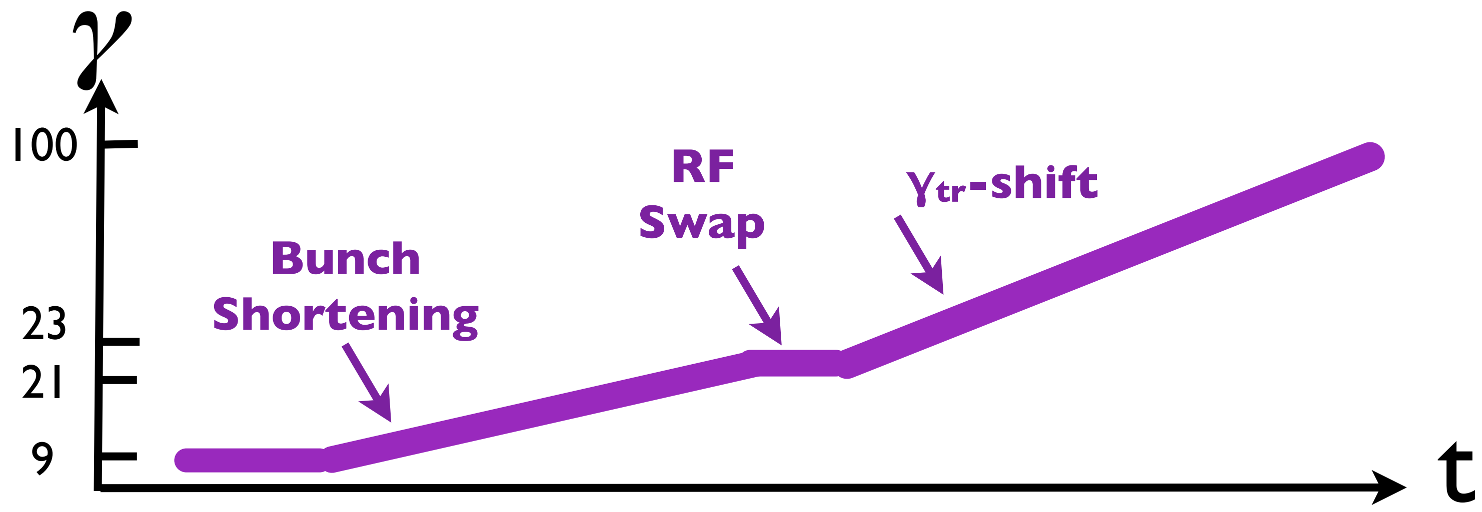
- **SPS Injection**
  - **Fast injection of 20 bunches**
  - **< 10% of SPS filled**
  - **PS needs long bunches due to space charge** (which is worse for low energy)
  - **An 1 MV 40 MHz** (h=924) **RF system (added) will retrieve these bunches**
  - **Bunch shortening needed for DR injection**
  - **Then RF swap to existing 8 MV 200 MHz** (h=4620) **RF system**



- **SPS Acceleration**
  - **to γ = 100**

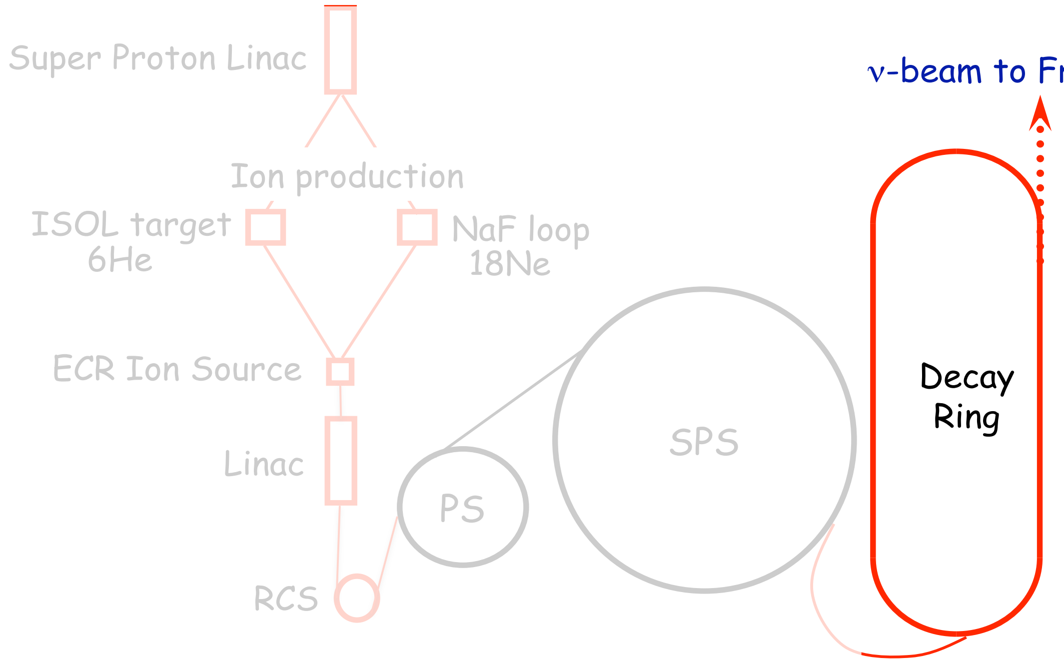
    → $B\rho$ = 559.3 Tm (^{18}Ne)
    934.8 Tm (^{6}He)

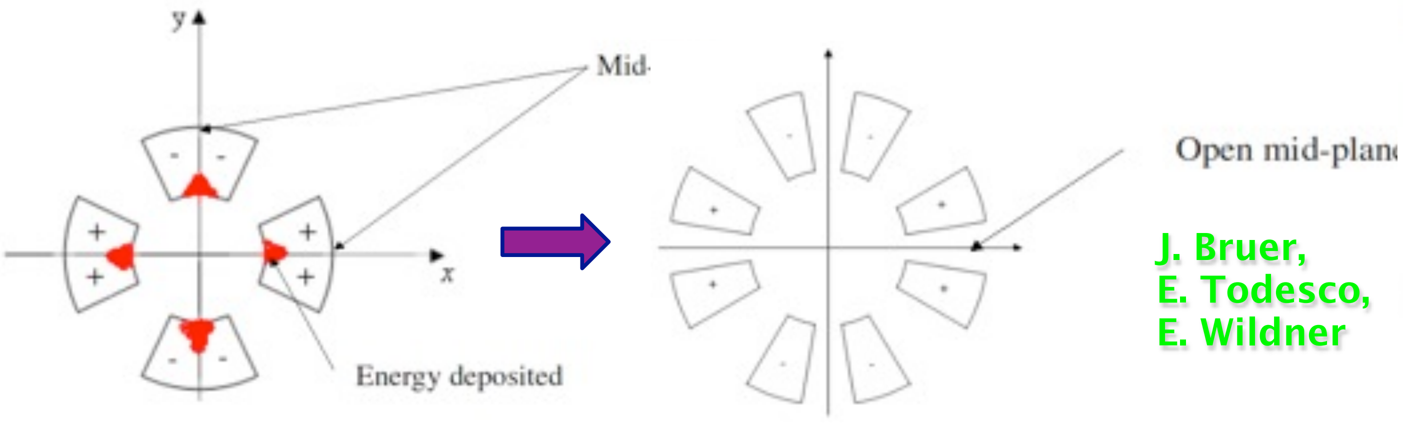
    (not SPS max)



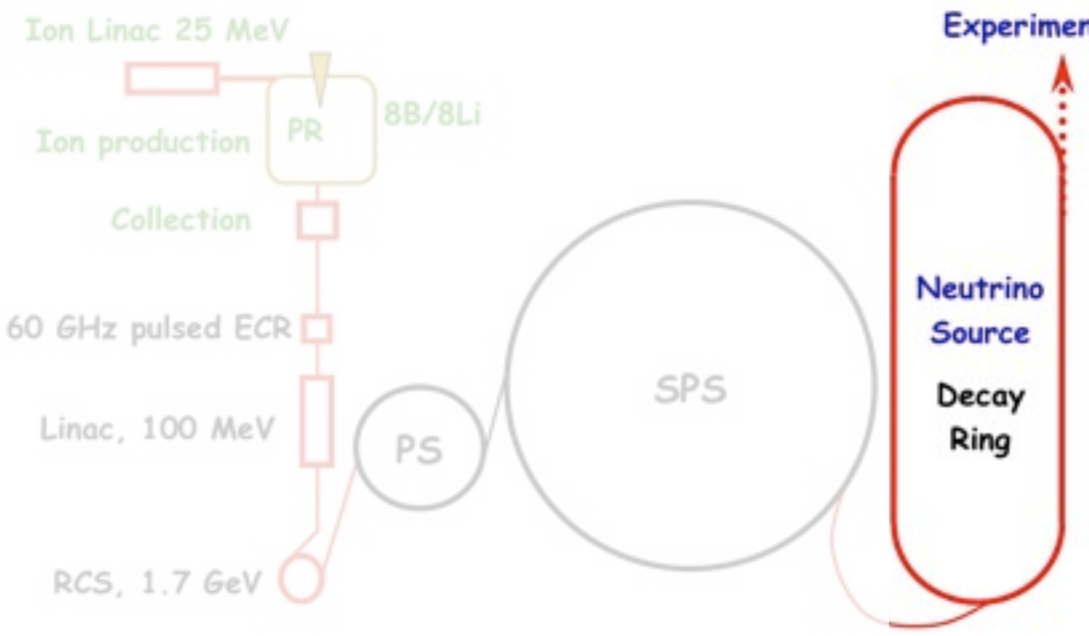
DR - Decay Ring

- **For both Baselines:**
  - Circumference = 6911.6m & L_{eff} = 39%
  - Bending radii ρ = 121m → B = 7.7T ($^{6}He^{2+}$), 4.6T ($^{18}Ne^{10+}$), 6.9T ($^{8}Li^{3+}$), 4.1T ($^{8}B^{5+}$)
  - Superconducting → Open mid-plane quadrupole magnets to avoid quenching due to energy depositions from decay products





J. Bruer,
E. Todesco,
E. Wildner



  - All ions with γ = 100 → E_{tot} = 560.6GeV ($^{6}He^{2+}$), 1676.7GeV ($^{18}Ne^{10+}$), 747.1GeV ($^{8}Li^{3+}$), 747.2GeV ($^{8}B^{5+}$)

  - Focusing of neutrinos; opening angle < 1/γ

$R_\perp$ of the DR

Private Discussions with G. Rumolo

- Detailed calculations of Transversal Shunt Impedance, $R_\perp$, require design assumptions of ALL DR components, instead:
- **Let's estimate $R_\perp^{DR}$ based on a machine with same circumference as DR; SPS ($R_\perp^{SPS}$ = 20 MΩ/m)**
  - ➡ **Modern, smooth design of the vacuum pipe compare to old SPS → *Improvement by factor 10***

    → $R_\perp^{DR} \sim 2$ MΩ/m
  - ➡ **The DR is a less general machine than the SPS** (not required to handle many type of beams)
  - ➡ **No need for as many kickers as SPS** (and modern kicker design) → ***Improvement by factor 2***

    → $R_\perp^{DR} \sim 1$ MΩ/m
- Further; in 20 years improved Broad Band Feedback System

3 Tools

- Three ways to find the Bunch Intensity Limit, N_b^{th}:
  - A multi-particle tracking program in time domain, “HEADTAIL”

    G. Rumolo et ali, CERN-SL-Note2002-036-AP
  - A theoretical program in frequency domain, “MOSES”

    Y.H.Chin CERN-LEP-TH/88-05
  - Peak current values into a coasting beam formula gives the “Coasting Beam Equation” (here for $\xi=0$):

$$N_{b_{x,y}}^{th} = \frac{32}{3\sqrt{2}\pi} \frac{R|\eta|\varepsilon_l^{2\sigma}\omega_r}{\langle\beta\rangle_{x,y} Z^2\beta^2 c R_\perp}$$

E. Métral, CERN, Overview of Single-Beam Coherent Instabilities in Circular Accelerators

$R_\perp$ = “Shunt Impedance” (see next slide)